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REVIEW OF TURBOFAN-ENGINE COMBUSTION AND JET-NOISE RESEARCH AND--ETC(U)

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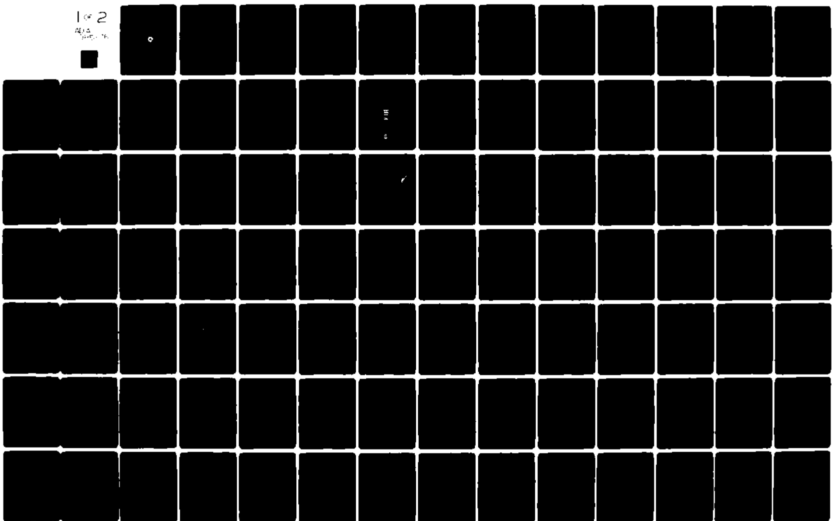

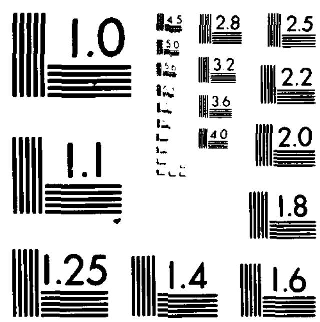

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Report No. FAA-RD-80-16

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LEVEL II

REVIEW OF TURBOFAN-ENGINE COMBUSTION- AND JET-NOISE RESEARCH AND RELATED TOPICS

ADA085176

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and
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DEPARTMENT OF TRANSPORTATION • UNITED STATES OF AMERICA

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16. Abstract

In the early 1970s, internal sources of noise in jet engines were identified as being potentially strong enough to affect the levels of jet-aircraft noise at the Far Part 36 noise-certification points. These internal sources have a broadband spectrum and are not related to the rotating turbomachinery components within the engine. A review of the status of jet- and core-engine noise research was held at FAA Headquarters in the Fall of 1974. Subsequent to that status review, the FAA sponsored additional studies of combustion noise. Also, during this period, a significant study of jet noise produced by high-velocity jets was conducted under the initial sponsorship of DOT, and then of FAA. The high-velocity jet-noise study included extensive analytical and experimental investigations of jet-noise suppressors as well as studies of the effects of forward motion on jet-engine noise.

In February 1977, the FAA and the DOT held a second Conference at FAA Headquarters to review the status of jet- and combustion-noise research. The Conference was attended by representatives from Government and Industry and presentations were made of contracted and independent research studies. This report reviews the research findings presented at the February 1977 Jet/Combustion-Noise Research Conference as well as subsequent to the Conference through June 1979.

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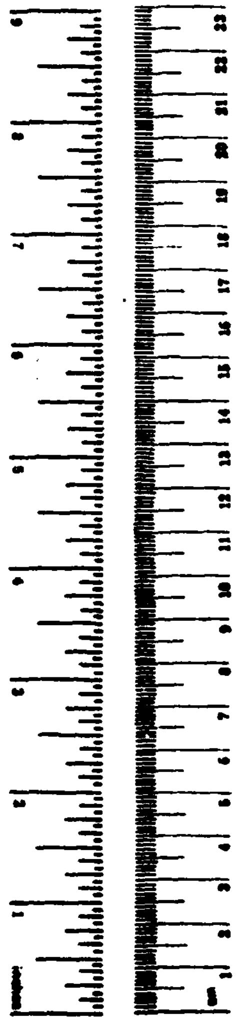
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

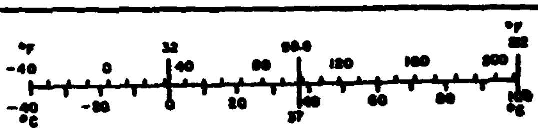
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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REVIEW OF TURBOFAN-ENGINE COMBUSTION- AND JET-NOISE RESEARCH AND RELATED TOPICS

by

Alan H. Marsh and Gary L. Blankenship

1. INTRODUCTION

The turbojet-powered long-range commercial jet transports introduced in the late 1950s operated with supersonic jet exhaust velocities during takeoff. The corresponding high levels of jet noise coupled with moderate climb capabilities combined to produce significant noise exposure around the airports where the aircraft were operated. To alleviate the jet-noise problem, the aircraft industry devoted substantial efforts to understand the physical mechanisms that are the source of the noise and to develop means to reduce the impact on airport communities.

Introduction of turbofan-powered aircraft in the early 1960s as a means of reducing fuel consumption and increasing range was accompanied by a reduction of the jet noise levels at the same thrust because of the increased mass flow at a lower jet velocity. Turbomachinery noise from the fan stages was, however, very noticeable especially during landing approach. The advent of noise-certification regulations in the late 1960s caused a significant increase in the research and development efforts to understand the sources of noise produced by jet engines and to control them. The effort to begin the development of a U.S. Supersonic Jet Transport in the 1960s also led to significant research on jet noise.

High-bypass-ratio turbofan engines were introduced into commercial service in the late 1960s. These engines, and their modern growth versions, have become the powerplants for the larger-capacity transcontinental and

intercontinental aircraft. Turbomachinery noise from the high-bypass-ratio engines is controlled by the careful selection of engine design parameters and by the installation of acoustically absorptive treatment on the walls of the inlet and exhaust ducts.

Future versions of high-bypass-ratio turbofan engines are expected to have relatively low levels of fan and turbine noise because of the incorporation of advanced concepts to minimize the generation of noise at the source and the installation of more-effective acoustically absorptive duct linings. Jet noise levels will be minimized by the selection of engine cycle parameters that permit meeting aerodynamic and propulsive design requirements with the lowest feasible primary and secondary jet exhaust velocities. Advanced engines may use an internal mixer nozzle on the exhaust of the primary nozzle in a long-duct mixed-flow arrangement to achieve improved fuel efficiency and lower jet noise levels.

As a result of the reductions in turbomachinery and jet noise expected for future turbofan engines, it was predicted in the early 1970s that combustion noise (or core engine noise as it was then termed) could be a major contributor to the total aircraft noise level at the takeoff and approach conditions of Part 36 of the Federal Aviation Regulations for aircraft noise type certification, especially when thrust cutback during climbout was used to demonstrate compliance with the takeoff noise requirement. Predicted levels of combustion noise were considered to be high enough that some projected future aircraft were anticipated to not be able to meet future aircraft noise certification requirements which were expected to be lower than the 1969 requirements. These concerns about combustion noise were voiced for turbofan engines intended for jet transports designed for both conventional takeoff and landing (CTOL) and short takeoff and landing (STOL). Engines for STOL aircraft would probably have higher bypass ratios, possibly with a geared fan, and hence lower jet noise and relatively more combustion noise than engines for future CTOL aircraft. Combustion noise was thus identified as an important engine noise source which needed to be studied, in addition to sources of jet noise and turbomachinery noise, in order to be able to develop economically reasonable and technologically practicable aircraft-noise-certification requirements for future jet transports.

In light of these considerations, the FAA in 1972 initiated a research program to identify the sources of combustion noise (and other internal noise sources), evaluate possible noise-suppression methods, and develop a prediction program. In the Fall of 1974, a status review of research in core noise and jet noise was held at FAA Headquarters in Washington, DC. Presentations were made by U.S. and European investigators from industry and government. The principal core-noise contractor was the General Electric Company in Evendale, OH.

A conclusion of the 1974 Status Review was that the scheme developed by GE in 1973/74 for predicting the level and directivity of direct combustion noise was not universally applicable and did not apply to combustor systems in engines made by other manufacturers. It was also felt that the data available to develop the prediction method would probably not be applicable to advanced combustor concepts designed to meet requirements from the Environmental Protection Agency for noxious emissions from future engines, nor to the advanced combustor concepts for improved fuel efficiency for future engines.

In 1975, the FAA contracted with GE and with the Pratt & Whitney Aircraft Division of United Technologies Corporation (P&WA) for additional studies of the generation, suppression, and prediction of combustion noise. To supplement the studies of so-called direct combustion noise, the FAA also contracted with the Georgia Institute of Technology (GIT) for studies of so-called indirect sources of combustion noise, namely temperature inhomogeneities (entropy fluctuations) passing through the turbine stages and interactions between axial velocity fluctuations and the nozzle exit (vorticity fluctuations).

In addition, as part of the total core-engine noise research program, the FAA also contracted with GE for a study of the attenuation of turbine noise (the discrete-frequency and broadband components) as it propagates through the various rotor and stator stages of the high-speed (high-pressure) and low-speed (low-pressure) turbines.

Furthermore, in addition to the above efforts related to combustion and turbine noise, the FAA had supported a significant amount of research for several years at GE and at The Boeing Company concerned with the generation, suppression, and prediction of the noise produced by high-velocity jets. The impetus for this jet noise research was the U.S. supersonic transport program in the 1960s and early 1970s. As an outgrowth of the high-velocity jet noise studies, research was initiated on methods of reducing jet noise generated by the exhaust flows from turbofan engines for subsonic jet transports. The research included studies of the noise produced by separate-flow exhaust systems, with fan-exhaust ducts of various length including co-planar, as well as mixed-flow arrangements with confluent-flow and forced-mixing nozzles on the turbine-exhaust duct.

As a follow-up to the Status Review of 1974, the FAA organized a second conference at FAA Headquarters in Washington, DC from 22 to 24 February 1977. At this second Status Review, participants from industry and government agencies in the U.S. and Europe again met to present results of their own investigations and to review presentations of the work performed by the FAA contractors. Most of the presentations at the 1977 Status Review were concerned with jet noise, though the first day was devoted mainly to discussions of combustion noise. Other topics discussed included nonlinear atmospheric propagation, and the noise produced by blown-flap STOL-airplane concepts.

This report was prepared to summarize the principal presentations that were made at the February 1977 Status Review. The report is divided into four main sections that contain reviews of (1) combustion noise generation and prediction; (2) jet noise generation, suppression and prediction; (3) flight effects on jet and combustion noise; and (4) related topics. Reviews of the combustion and jet noise presentations begin with discussion of some of the relevant research conducted prior to the February 1977 Status Review. Some results presented in selected reports published after the February 1977 Status Review are also included here to enhance and update the discussions.

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2. COMBUSTION NOISE

2.1 Background

Combustion noise was first seen as a source of low-frequency engine noise in excess of the jet-noise level predicted by extrapolating the method of the Society of Automotive Engineers (SAE) AIR 876[1] to exit velocities below 1000 ft/s. Whereas, the extrapolated SAE jet noise levels followed a near eighth power dependence on jet velocity, the measured noise levels from a variety of turbofan engines exhibited more-nearly a fifth power dependence as shown in Figure 1. The resulting "excess" noise has been attributed to various sources, including the following:

- direct combustion noise resulting from pressure unsteadiness due to heat fluctuations in the combustion process;
- indirect combustion noise resulting from interactions between the rotor and stator stages of the turbine and convected temperature (entropy) and velocity (vorticity) fluctuations;
- turbulent and swirling flow interacting with support struts downstream of the final turbine stage; and
- noise generated at the nozzle exit lip by interaction with velocity fluctuations.

In general, these and other sources upstream of the jet exit have come to be described as "core" engine noise or more recently "internal" noise.

The significance of core noise to other gas turbine engine sources is illustrated in Figure 2. Core engine noise could well establish a noise "floor" for the next generation of aircraft gas turbine engines due to improvements in acoustic liners for the fan and primary ducts, development of higher-bypass-ratio engine cycles, and the use of internal mixers. The need for core noise technology development led to various programs[2-24] concerned with source identification, prediction, and suppression techniques.

Identification of the dominant source(s) of internal engine noise required substantial experimental data. Separating the effects of flow swirl on turbulence interaction with downstream obstructions from jet

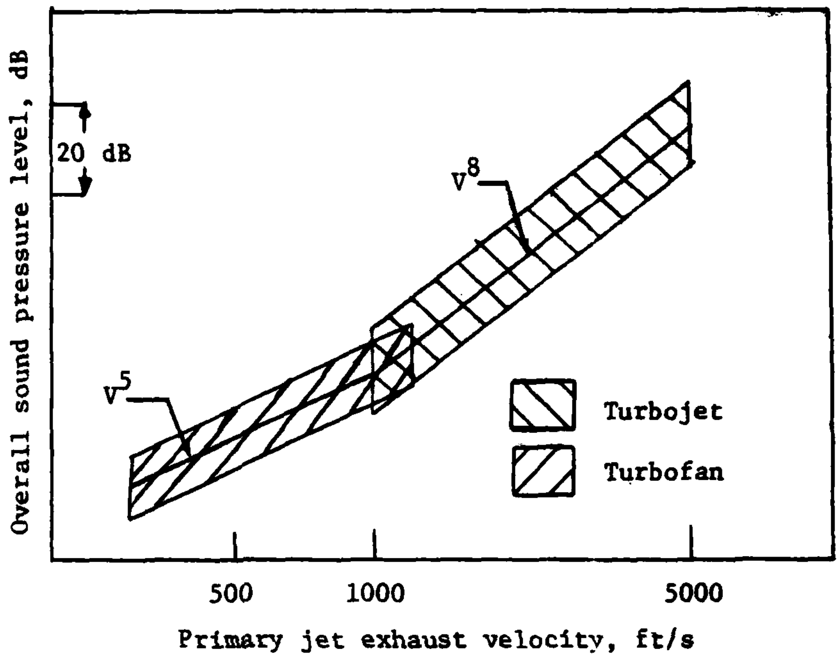

Figure 1. - Turbojet and turbofan jet/combustion noise.

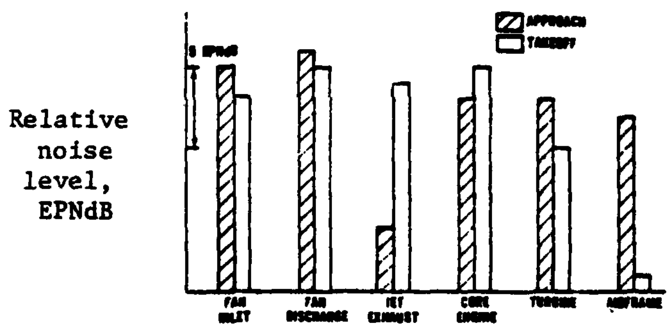

Figure 2. - Typical high-bypass-ratio-engine component noise distribution, ref. 2.

exhaust noise posed a difficult experimental problem due to similarities in spectra and directivity. Exhaust struts, which provide structural support and aid in eliminating exhaust swirl, are designed for small incidence angles at design engine speed. At low engine speeds, as at aircraft approach power settings, the turbine is operating off-design. As a result, large flow-incidence angles are incurred resulting in noise generation by velocity fluctuations due to flow separations. Noise can also be generated by fluctuating lift forces resulting from turbulence in the flow impacting on the exhaust struts with random angles of incidence. Furthermore, noise can be generated by momentum fluctuations in the exhaust flow over the nozzle lip. It has been argued[3,4] that the above mentioned flow disturbances interacting with downstream obstructions will give rise to dipole noise resulting in a V_j^6 dependence which would mask the V_j^8 dependence of jet noise at low flow velocities.

Of the several possible sources of internal engine noise, the dominant mechanisms of noise generation are generally attributed to the combustion process[5-8]. Combustion noise arises for two reasons: (1) combustors have a working fluid in turbulent motion and (2) there is significant heat release. The random flow and unsteady pressure fluctuations are inherent noise sources. Experimental studies on full-scale engines[9] have used cross-correlation techniques and demonstrated that, at low engine power settings, a substantial portion of the measured low frequency noise in the far field is generated by the combustor. The two most-probable causes for internal engine noise are the direct and indirect mechanisms mentioned above. In 1979, separation of these two noise mechanisms was still the subject of considerable controversy. Direct combustion noise is the result of unsteady burning while indirect combustion noise results from the convection of "hot spots" (temperature inhomogeneities) through pressure gradients downstream of the combustor. As both mechanisms arise from the same process — fluctuations in heat release — they are highly correlated and pose a difficult problem in determining their relative importance to internal engine noise.

The objective of a combustion noise prediction procedure is to establish the dependence of combustion noise on pertinent performance and geometric parameters and the effect of downstream obstructions. Such a prediction

technique could then be used to design a quieter combustor fitting the same plenum, delivering equal or better performance, and, ideally, emitting fewer pollutants.

Before discussing the state-of-the-art in combustion noise prediction as presented at the 1977 DOT/FAA Combustion Noise-Jet Noise Status Review, it is pertinent to survey the background which forms the basis of previous prediction techniques. Various authors have used a variety of systems for designating engine stations in the expressions for sound power level, $\bar{L}_W$, and sound pressure level, L_P. For consistency, it was decided to present the various expressions in this review using the terminology in Fig. 3 for engine station numbers. Sound power levels are given in dB re 1 pW and sound pressure levels are given in dB re 20 μPa. The various quantities in the expressions are in consistent units. Pressures and temperatures are measured on an absolute scale. A list of consistent symbols and nomenclature is given in Table I for the various expressions used to describe combustion noise.

Initial studies of the mechanisms of combustion noise generation were confined to the study of open flames. Theoretical studies, such as by Chiu and Summerfield[10], produced complex expressions involving flame characteristics and requiring sophisticated measuring equipment. As a simpler approach, Strahle[11] derived a combustion noise theory also based on results using open flames. The theory offered meaningful engineering expressions in terms of well-understood steady-state variables. As an extension, Strahle[12] derived an expression for the far field noise from an open flame in terms of a volume integral of the time derivative of the heat release rate in the combustor. Based on correlations of combustor rig data, the theory suggested a scaling law of the following form

$$L_W = K_1 + 10 \log [(1/(T_4{}^2\sqrt{T_5})) P_5 f^a V_c{}^2 D_c{}^2], \qquad (1)$$

where $0 \leq a \leq 1$ for lean to rich burning.

Strahle's scaling law has since led to engineering methods developed throughout the industry for application to prediction of noise from actual aircraft engine combustors.

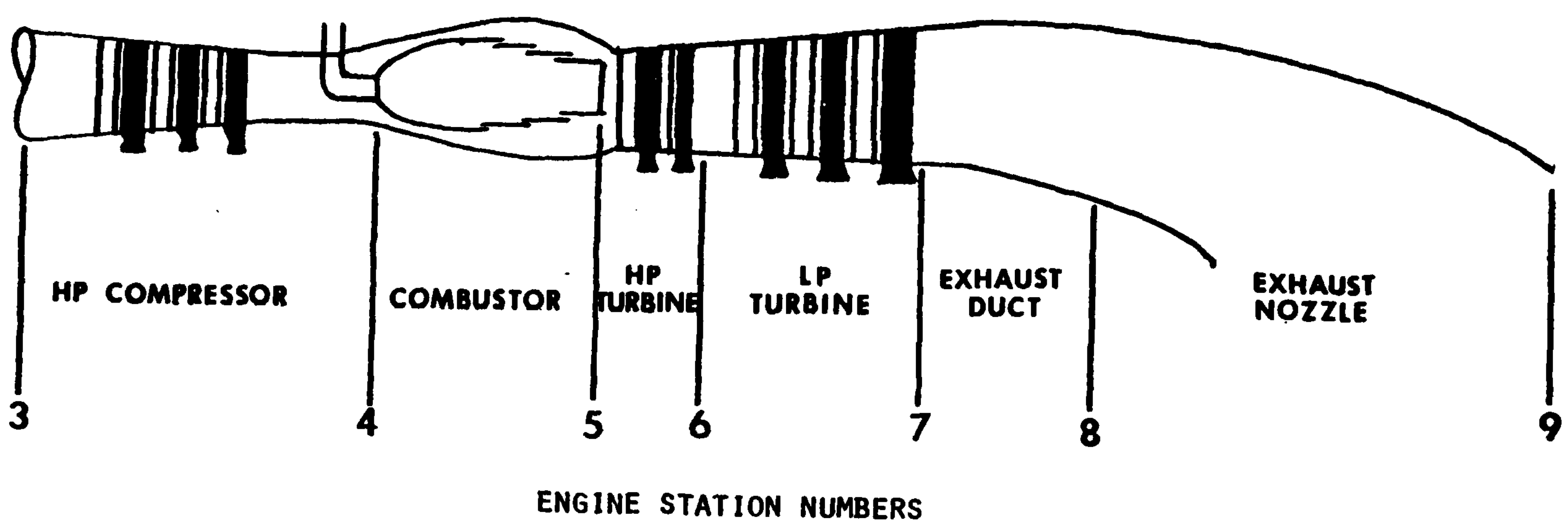

Figure 3. - Numbering system for engine station numbers.

Table 1.-Combustion-Noise Nomenclature

A	area
c_p	specific heat at constant pressure
D	combustor dimension
f	fuel to air ratio
F	frequency
H	fuel heating value
K	experimental constant
L	length
$\dot{M}$	mass flow rate
N	number of nozzles
P	total pressure
$\overline{P}$	steady-state pressure
R	gas constant
T	total temperature
V	velocity
δ	combustor pressure ratio, P_5/P_0
θ	combustor temperature ratio, T_5/T_0
ρ	density

Subscripts

a	air
c	combustor
D	exhaust duct
e	exit plane
0	ambient
3	HP compressor inlet
4	combustor inlet
5	combustor exit
6	LP turbine inlet
7	LP turbine exit
8	nozzle inlet
9	nozzle exit
st	stoichiometric

Superscripts

n, q	experimental constants

Gerend, Kumasaka, and Roundhill[7], based on farfield measurements at low engine power settings of high-bypass-ratio turbofan engines, developed an empirical procedure to predict the overall sound pressure level at 110° on a 200-ft sideline as a function of parameters downstream of the combustor

$$L_p = K_2 + 10 \log [T_5^2 (\dot{M}_5 \sqrt{\theta_5}/\delta_5)(P_7/P_5)^n]. \tag{2}$$

Ho and Tedrick[9] presented a prediction technique for combustor noise in auxiliary power units in terms of sound power

$$L_W = K_3 + 10 \log [(T_5 - T_4)(V_c D_c)^{1/2}(1 + f)(P_4/T_4)^{1/2}]^q, \tag{3}$$

where $q = 2$ for combustor rigs
$= 4$ for APU or engine.

The correlation in Eq. (3), like that in Eq. (1), implied that combustion noise is dependent upon actual combustor parameters in addition to downstream effects.

A model of the noise generated by a combustor, developed by the General Electric Company[13], showed the acoustic power level as a product of the thermal power input and the thermal/acoustical conversion efficiency. Thermal power input is proportional to the heat release rate. Conversion efficiency is proportional to the temperature rise across the combustor. Through consideration of engine data, the effect of combustion at higher than atmospheric pressures and temperatures was accounted for by a ratio of densities as

$$L_W = K_4 + 10 \log [\dot{M}_{a,c} (T_5 - T_4)^2 (\rho_4/\rho_0)^2] \tag{4}$$

where K_4 = 48 for turbofan engines
= 56 for turboshaft engines
= 64 for turbojet engines.

In the determination of the experimental constant, K_4 in Eq. (4), it was noted that the engines with the smallest temperature drop across the turbine produced the greatest noise levels in the farfield. It was therefore postulated that the attenuation of the pressure fluctuations after propagation through the turbine may be important in determining the farfield combustion noise level.

Several problem areas existed in the various procedures for predicting combustion noise levels from actual engines. The first empirical correlations were derived as a result of theoretical considerations and experimental data from combustor rigs. The empirical techniques failed, however, to explain observed differences of as much as 20 dB between the sound power levels generated by combustor rigs and full scale engines. In particular, adequate models for the attenuation through the turbine and exhaust nozzle as well as for the combustor-noise peak frequency were needed. Considerable controversy has accompanied attempts to develop a universal expression for the peak frequency of the combustor noise spectrum that would be applicable to various combustor geometries and performance parameters.

Under contract to the FAA, the General Electric Company undertook a detailed investigation of internal engine noise[5]. Completed in 1974, the program made significant improvements in the understanding and ability to predict combustion noise. Originally, a semi-empirical correlation as shown in Figure 4 yielded three separate lines for noise data from three engine types — turbojet, turboshaft, and turbofan. However, a turbine attenuation model was later developed by GE[14] and was found to collapse the three-line correlation into a single line prediction as shown in Figure 5

$$L_W = K_5 + 10 \log [\dot{M}_{a,c} (T_5 - T_4)^2 (\rho_4/\rho_0)^2 (T_5 - T_7)^{-4}_{design}] \qquad (5)$$

The above correlation was shown to be in good agreement with GE, Garrett/AiResearch, P&WA, and Boeing data.

2.2 Review of Combustion Noise Presentations at the 1977 DOT/FAA Conference

As part of an FAA Contract, Mathews,[15] et al. developed a more-detailed and comprehensive prediction procedure for direct combustion noise from turbo-propulsion systems. The prediction procedure presented analytical expressions for overall sound power level, peak frequency, and transmission loss in propagating through the turbine and exhaust nozzle. The expressions were derived in terms of readily measurable performance and geometry parameters. In addition, empirical spectra and directivity patterns were presented.

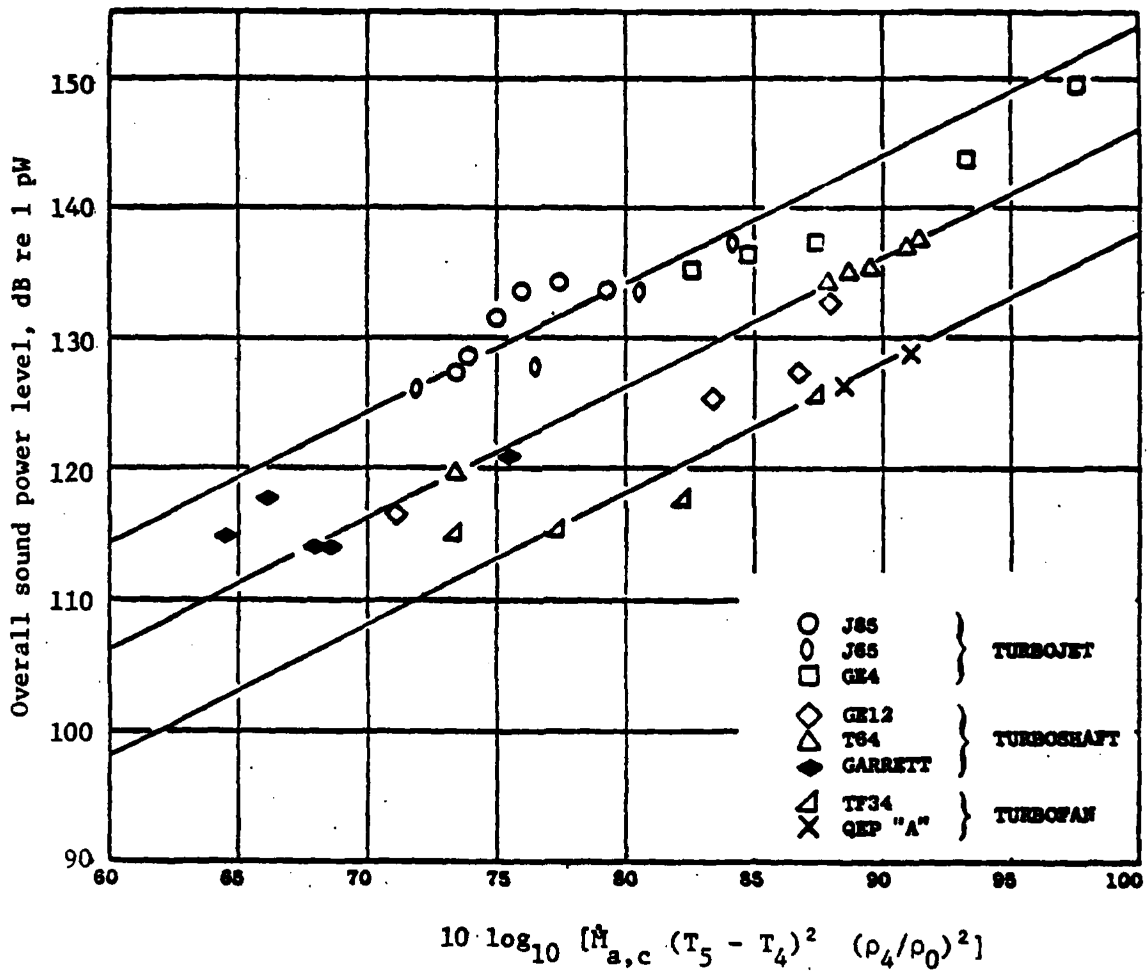

Figure 4. - Sound power levels from turboshaft engines as a function of the prediction parameter, ref. 5.

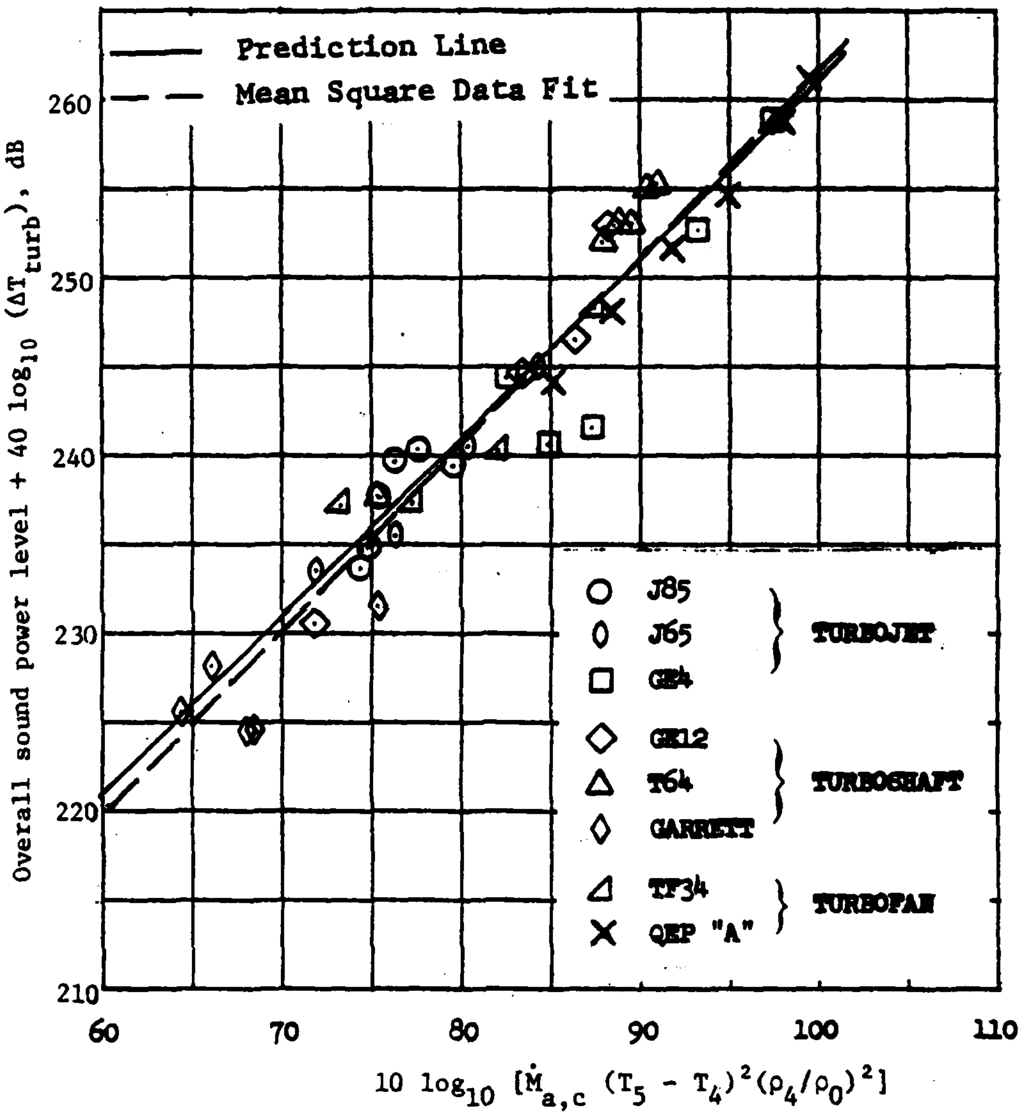

Figure 5. - Sound power level correlation for core noise, ref. 5.

An important facet of the model was the expression for the peak frequency of the combustion noise spectrum. The peak frequency was related to a typical reaction time for stoichiometric burning which is a function only of combustor geometry independent of combustor operating condition. The relation between peak frequency and reaction time was derived using conservation of mass and energy relationships within the reaction region and was given by

$$F_c = (K_6 R\ H_f/c_p)(\dot{M}_f/P_4)_{ref.}\ (1/A_c L_c). \tag{6}$$

The subscript ref. refers to the combustor reference design condition at takeoff power.

The two essential features of the expression in Eq. (6) for peak frequency were the inverse dependence on an equivalent internal combustor volume (length × typical cross-sectional area) and the inclusion of the empirical constant K_6 to account for differences between combustor types. The values of K_6 were given as 8 for can-type combustors and 3 for annular combustors.

The expression for overall sound power level in Ref. 15 was derived from Strahle's expression[12] for the farfield noise from an open flame. It is given by

$$\begin{aligned} L_w = K_7 &+ 10 \log [(1/N_f)\ A_c^{\,2}\ P_4^{\,2}\ (\dot{M}_{a,c}\ \sqrt{T_4}/P_4 A_c)^4] \\ &+ 10 \log [1 + (H_f f_{st}/c_p T_4)^2\ f_c^{\,2}]. \end{aligned} \tag{7}$$

The second term in Eq. (7) shows the inverse dependence of the sound power on the number of fuel nozzles, N_f, and the combustor cross-sectional area, A_c. The remainder of the terms involve combustor performance parameters (i) combustor pressure, (ii) combustor air flow, (iii) normalized combustor inlet temperature, and (iv) combustor fuel/air ratio. Figure 6 shows the correlation of P&WA engine and combustor rig data with the expression for overall sound power level. The fact that the combustion-noise sound power levels produced by actual turbofan engines were significantly lower than predicted by the extrapolation of the correlation line through the combustor rig data indicated that attenuation of the noise after propagation through

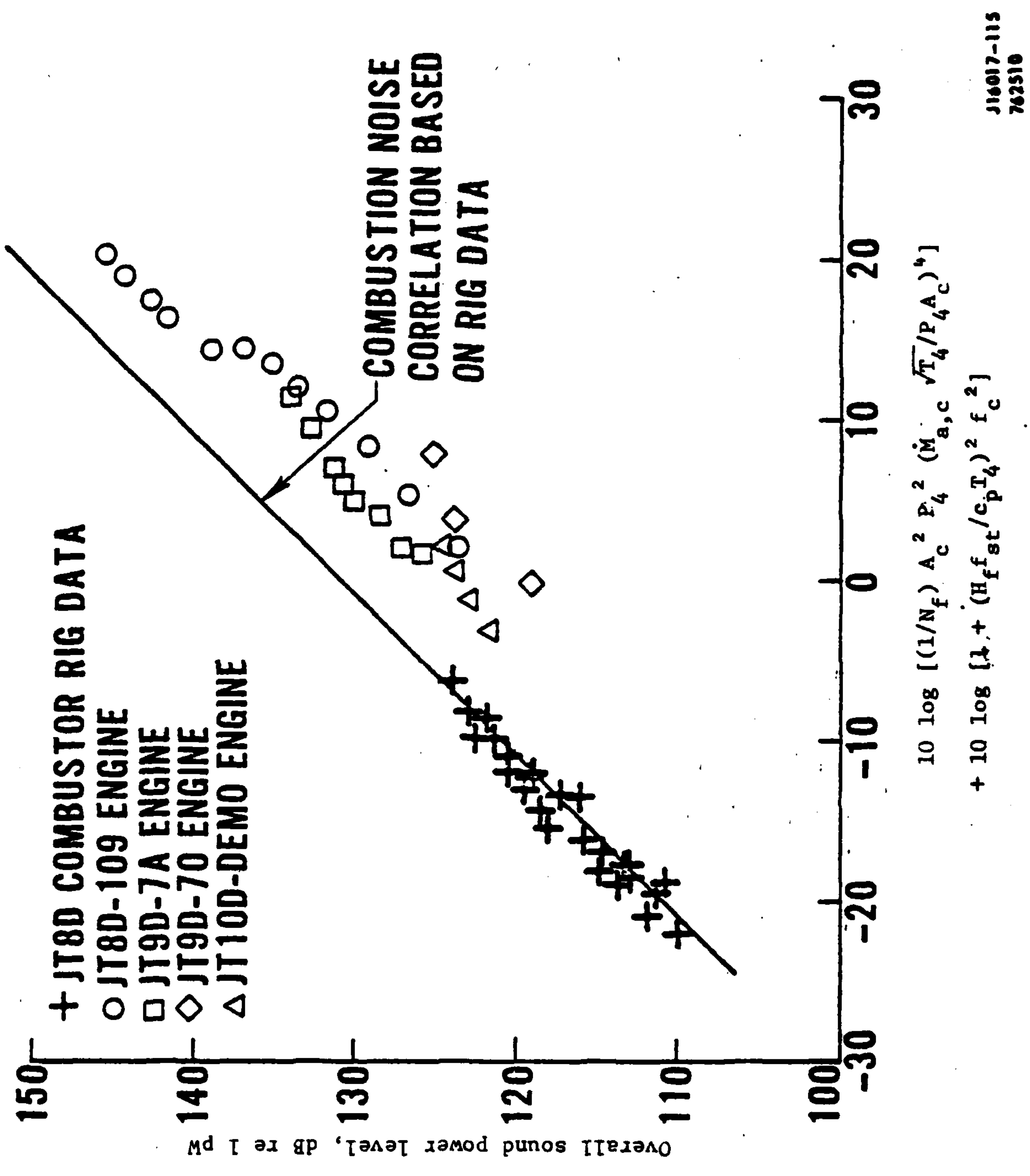

Figure 6. - Sound power levels from combustor rig and engine noise measurements, ref. 15.

the turbine stages and exhaust duct needed to be included in the prediction equation for sound power level.

A transmission-loss model was derived to relate the combustion noise produced by a combustor rig to that produced by combustors installed in actual engines. The model combines the attenuation mechanisms associated with propagation through the turbine stages and those associated with propagation down the exhaust duct and out the nozzle into the jet stream.

Using the assumption that the combustion noise consisted of plane waves, the analysis yielded an expression for attenuation through the exhaust duct that depended only on the ratio of the area at the combustor exit over which the combustor pressure fluctuations are correlated to the total annular area of the duct at the combustor exit. The result of the analysis for the model of transmission loss through the exhaust duct was given by

$$TL_{Duct} = 10 \log [\pi D_D/L_{Perimeter}] = 10 \log (1/0.23). \qquad (8)$$

An expression for the transmission loss through the turbine was derived by modeling the turbine as a discontinuity in the duct with a characteristic impedance. The transmission loss was determined by the ratio of the incident to the tramsmitted power and was given by

$$TL_{Turbine} = 10 \log [(1 + f)^2/4f] \qquad (9)$$

where: $f = (P_5/P_7) \sqrt{T_7/T_5}$. The total transmission loss through the duct and turbine is seen to be independent of frequency. Figure 7 shows that, by adding the total transmission loss term to that for the sound power level, the P&WA combustor rig and engine data collapsed to a single prediction line with less than a 2 dB standard deviation. To complete the prediction procedure, normalized combustion noise directivity and spectra shown in Figures 8 and 9 were derived from measured engine and rig data.

The results of the FAA-sponsored Core-Engine Noise-Control Program[5] and the Experimental Clean Combustor Program sponsored by NASA with GE[16] and P&WA[17] identified several areas for further investigation into combustor source noise generation and propagation. The principal recommendations were to:

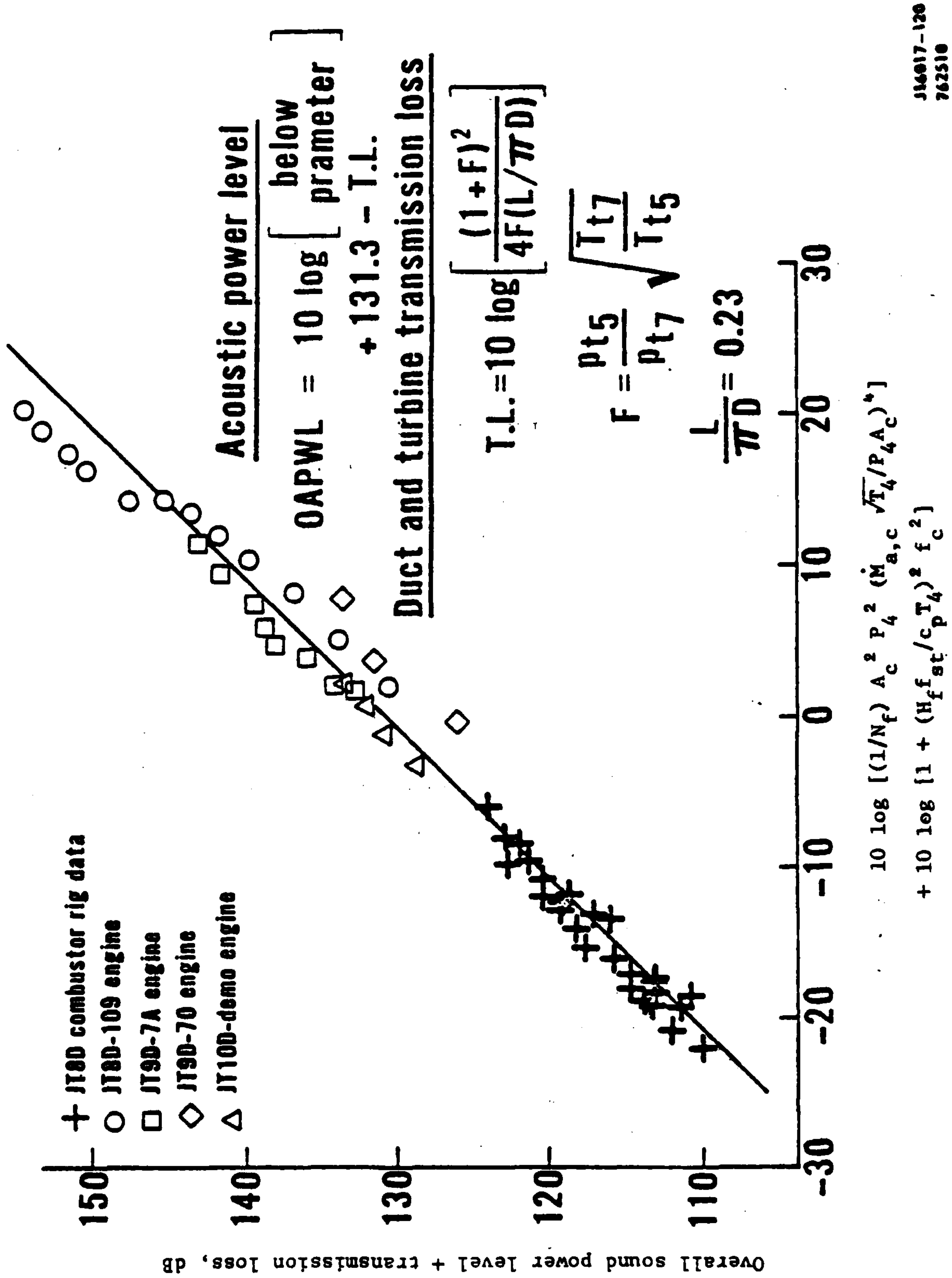

Figure 7. - Sound power level correlation for combustion noise, ref. 15.

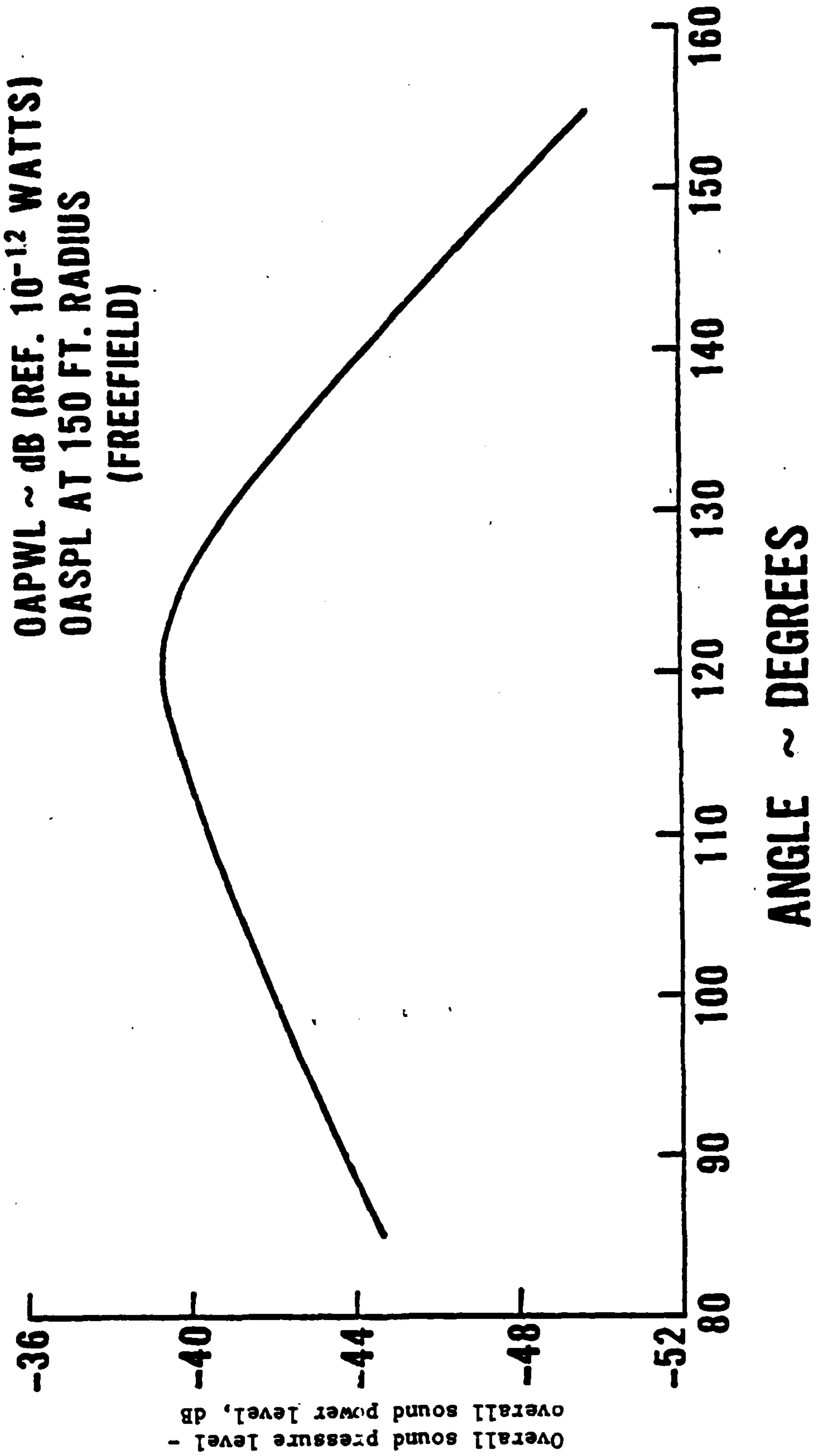

Figure 8. - Generalized combustion noise directivity, ref. 15.

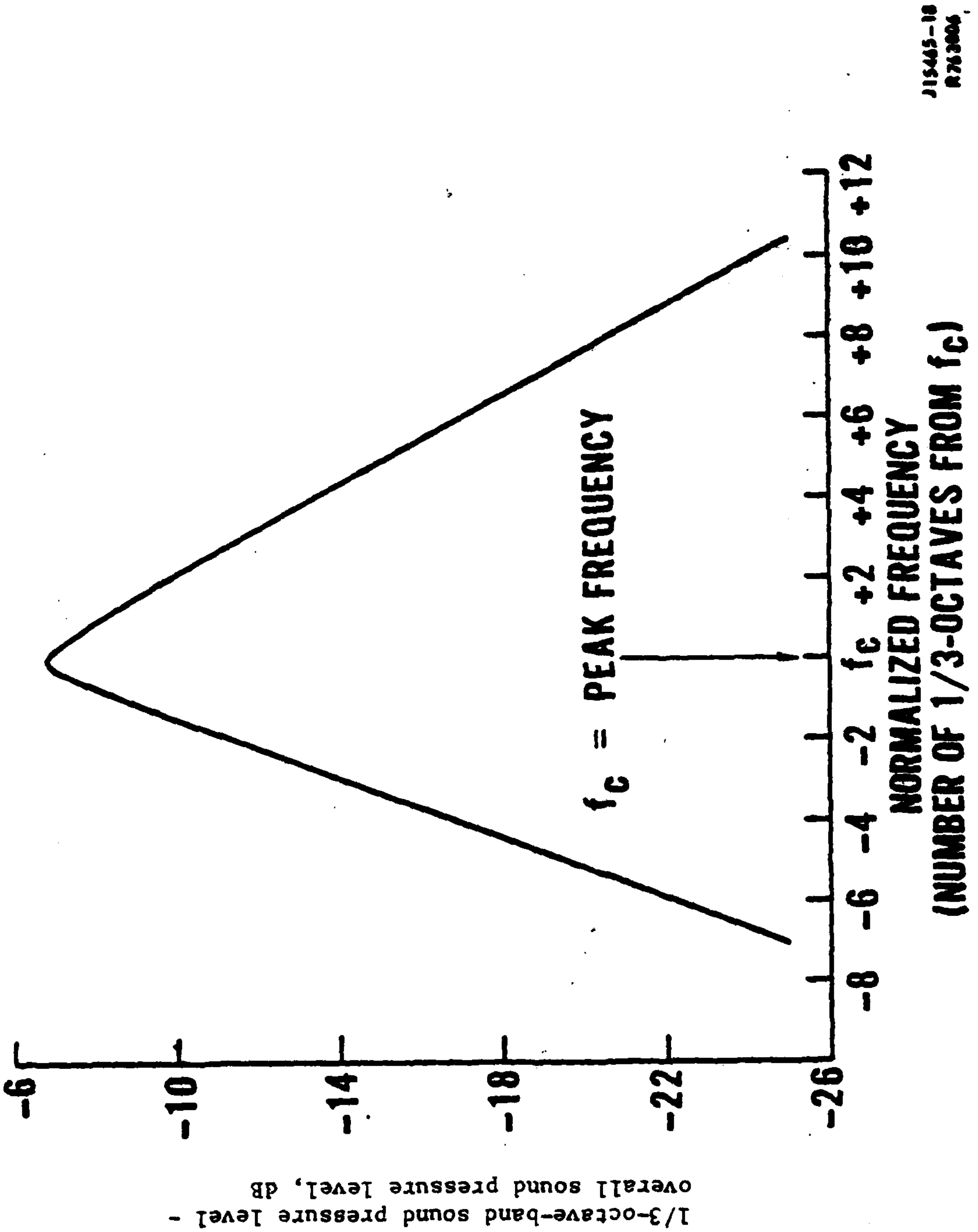

Figure 9. - Generalized combustion noise 1/3-octave-band spectrum, ref. 15.

- conduct a parametric study of advanced low-emission combustors relative to combustion noise
- determine the effect of exhaust nozzle geometry on farfield combustion noise
- extend the combustion-noise data base from actual engines to include turboshaft and turbofan engines with low-emission combustors
- determine the impact of emission-reduction techniques on combustion noise.

In response to these recommendations, the FAA initiated a study with GE[18] of the noise generated by low-emission engines. Under this study, combustion noise measurements were obtained for a double annular combustor, designated D13. The D13 combustor was the final configuration of the GE Experimental Clean Combustor Program.[16] The test data were input to a linear multiple regression analysis which yielded the following relationship for overall combustor sound power level

$$L_W = K_{10} + 10 \log [\dot{M}_{a,c} (T_5 - T_4) \sqrt{T_4}]. \qquad (10)$$

In performing the multiple regression analysis which led to Eq. (10), it was assumed that the relevant variables were combustor inlet pressure, mass flow rate, temperature rise, and combustor inlet temperature. However, subsequent parametric variations of temperature, pressure, and airflow yielded the following expression

$$L_W = K_{11} + 10 \log [(T_4{}^2/P_4{}^{1.5}) \dot{M}^3_{a,c}]_{constant} (T_5 - T_4). \qquad (11)$$

The difference between Eqs. (10) and (11) was attributed to the fact that one of the input quantities was not truly independent as required for a multiple regression analysis. The mass flow rate, $\dot{M}$ includes the product of density and velocity. Velocity is also related to the inlet pressure and temperature. The mass flow rate was thus replaced by a velocity term.[18] As a result the multiple regression analysis and the parametric results yielded similar relationships as given below with rounded exponents

$$L_W = K_{12} + 10 \log [(P_4/T_4)^{1.5} V_c{}^{3.5} A_c (T_5 - T_4)]. \qquad (12)$$

In comparison, Strahle's analytical scaling law[6] is of the following form

$$L_W = K_{13} + 10 \log [(1/T_4^2) V_c^4 A_c (T_5 - T_4)^{2a}], \tag{13}$$

where $0 \leq a \leq 1$ for lean to rich burning.

It was noted,[18] interestingly, that since current-production combustors use single fuel nozzles with 30 to 35% of the primary air used in combustion, a slightly rich burn occurs at full power, while at approach power the burn is slightly lean. As a result, optimization of combustion using dual nozzle systems, as suggested under the NASA/GE Experimental Clean Combustor Program[16], could be achieved over the entire operating range resulting in a lean burn and a lower exponent on the $(T_5 - T_4)$ term in Eq. (13) and hence lower combustion noise.

Figure 10 shows the correlation of overall sound power levels from the D13 advanced-technology combustor, the CF6-6 production combustor (measured outdoors) and power levels measured around indoor combustor rigs exhausting to ambient conditions. The good agreement with the correlating parameter of Eq. (12) indicated that (i) noise generated by combustors exhausting to ambient conditions is representative of that obtained at the elevated pressures and temperatures encountered in full scale engines and (ii) the clean-combustor data add substantially to the data base for noise-emission studies.

The next step after obtaining the correlation of sound power levels from combustor rigs was the correlation of full-scale engine data. Figure 11 shows the results for turboshaft, turbojet, and turbofan engine data. The engine data collapsed to two parallel lines different in slope and lower in amplitude than the correlation line from the rig data. A comparison of the combustor rig correlation and the earlier unified line prediction,[5] Eq. (4), which correlated engine data, showed that the functional relationships are similar:

$$L_{W,Rig} = K_{14a} + 10 \log [(P_4/T_4)^{1.5} V_c^{3.5} (T_5 - T_4) A_c] \tag{14a}$$

$$L_{W,Engine} = K_{14b} + 10 \log [\dot{M}_{a,c} (T_5 - T_4)^2 (\rho_4/\rho_0)^2]. \tag{14b}$$

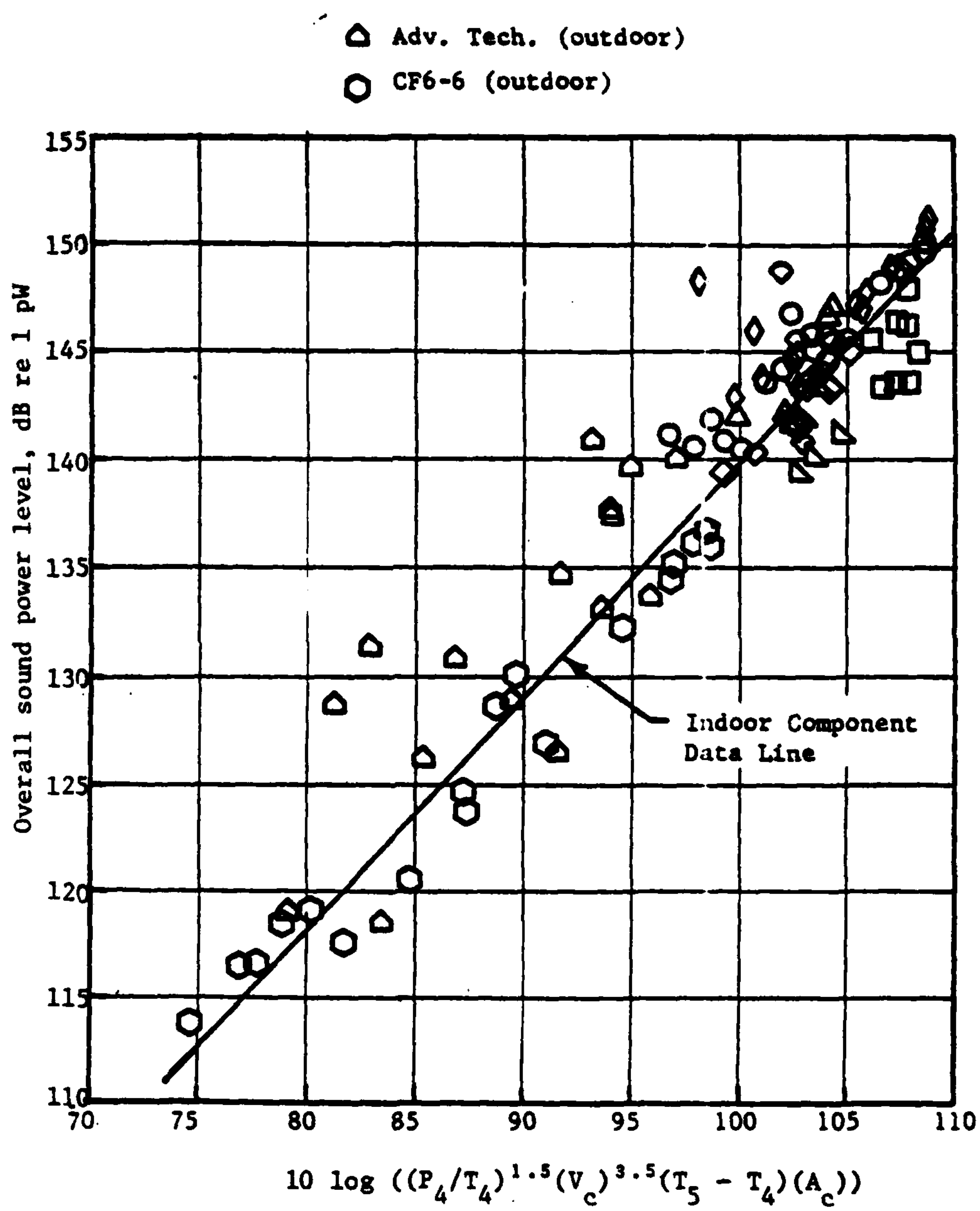

Figure 10.- Combustion noise correlation based on indoor and outdoor component data, ref. 18.

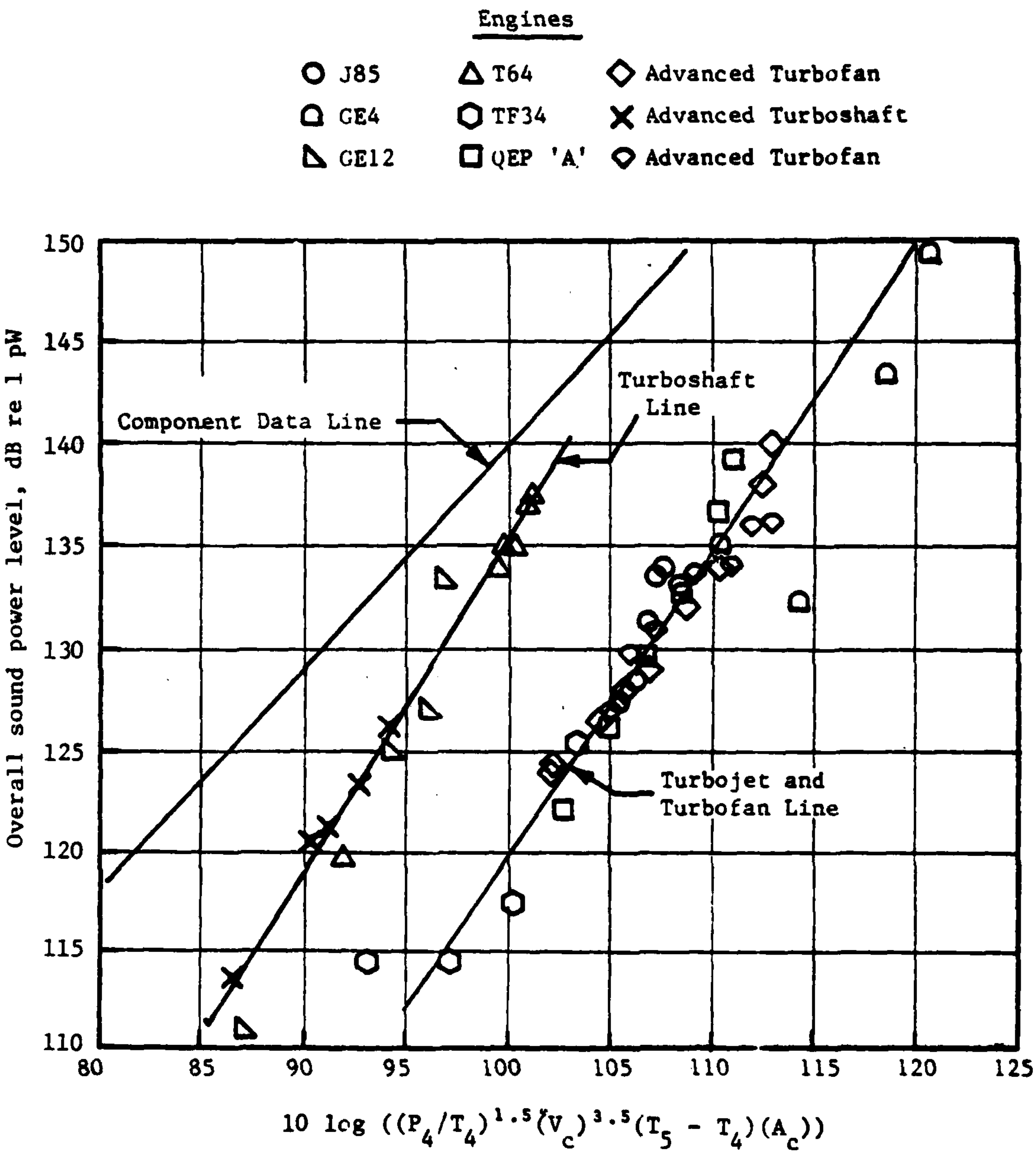

Figure 11. - Measured engine core noise levels as a function of rig correlation parameter, ref. 18.

Then, expressing the mass-flow-rate term as the product of density, area, and velocity and the temperature in terms of the square of velocity, the rig correlation parameter was, after some re-arranging, put into the following form

$$L_{W,Rig} = K_{15} + 10 \log [\dot{M}_{a,c} (T_5 - T_4)^2(\rho_4/\rho_0)^2(\sqrt{V_c}\ \rho_0{}^2/\rho_4{}^{1.5})]$$

$$= K_{15} + L_{W,Engine} + 10 \log (\sqrt{V_c}\ \rho_0{}^2/\rho_4{}^{1.5}). \qquad (15)$$

The last term in Eq. (15) is relatively constant over the operating range of an engine.

Because of the lack of agreement between the rig and engine data in Figure 11, the engine noise data were correlated using the unified-line correlating parameter from Eq. (5) and an approximation for the attenuation through the turbine and exhaust duct in the term $-40 \log (T_5 - T_9)_{design}$. The results reinforced the unified-line prediction as shown in Figure 12.

Another objective of the General Electric study[18] was to evaluate the effects on combustion noise resulting from changes to reduce noxious emissions. Although no quantitative results were presented, trends in the noise/emission relationship were offered. First, it was shown that the changes in emission levels and noise can be correlated using similar cycle parameters. Secondly, results with advanced low-emission combustors indicated that those combustors with the lowest emission levels also produced the highest noise levels. However, for typical engine cycles, it was also noted that the change in combustor noise is insignificant compared with the change in emission levels. The primary cause of increased noise with lower emission levels was attributed to higher velocities in the primary combustion zone.

Extensive measurements of internal pressure from a Lycoming YF-102 high-bypass-ratio turbofan engine were performed at NASA Lewis Research Center and reported by Reshotko, et al.[19] Acoustic waveguide probes were placed at the compressor exit, in the reverse flow combustor, at the turbine exit, and at the primary nozzle exit. Cross-correlation of the signals from two probes at the compressor exit showed a strong correlation at a time delay inconsistent with an acoustic wave propagation. The upstream signal

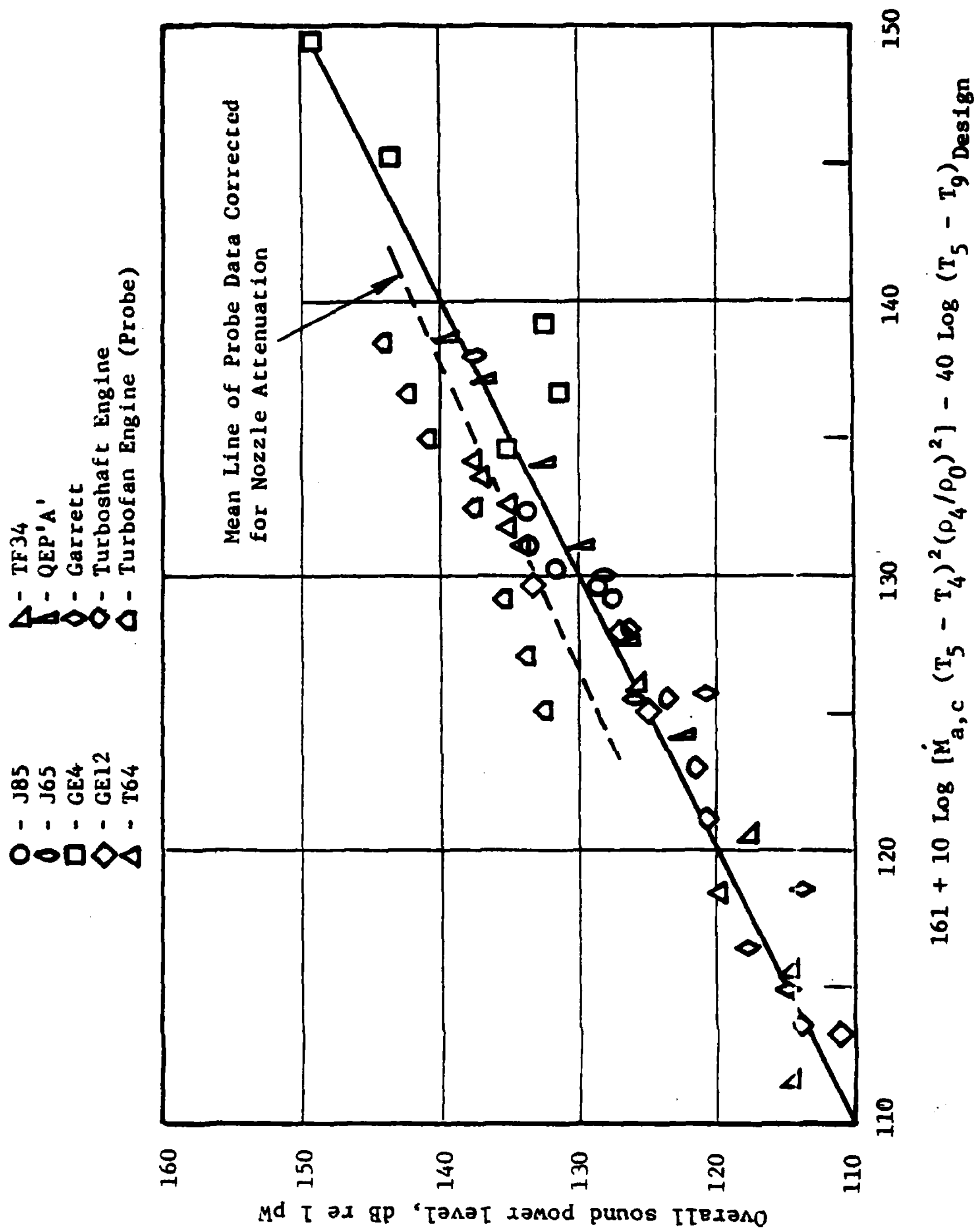

Figure 12. - Overall sound power level correlation for core-engine noise, ref. 18.

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$$L_{W,Rig} = K_{15} + 10 \log [\dot{M}_{a,c} (T_5 - T_4)^2 (\rho_4/\rho_0)^2 (\sqrt{V_c}\ \rho_0{}^2/\rho_4{}^{1.5})]$$
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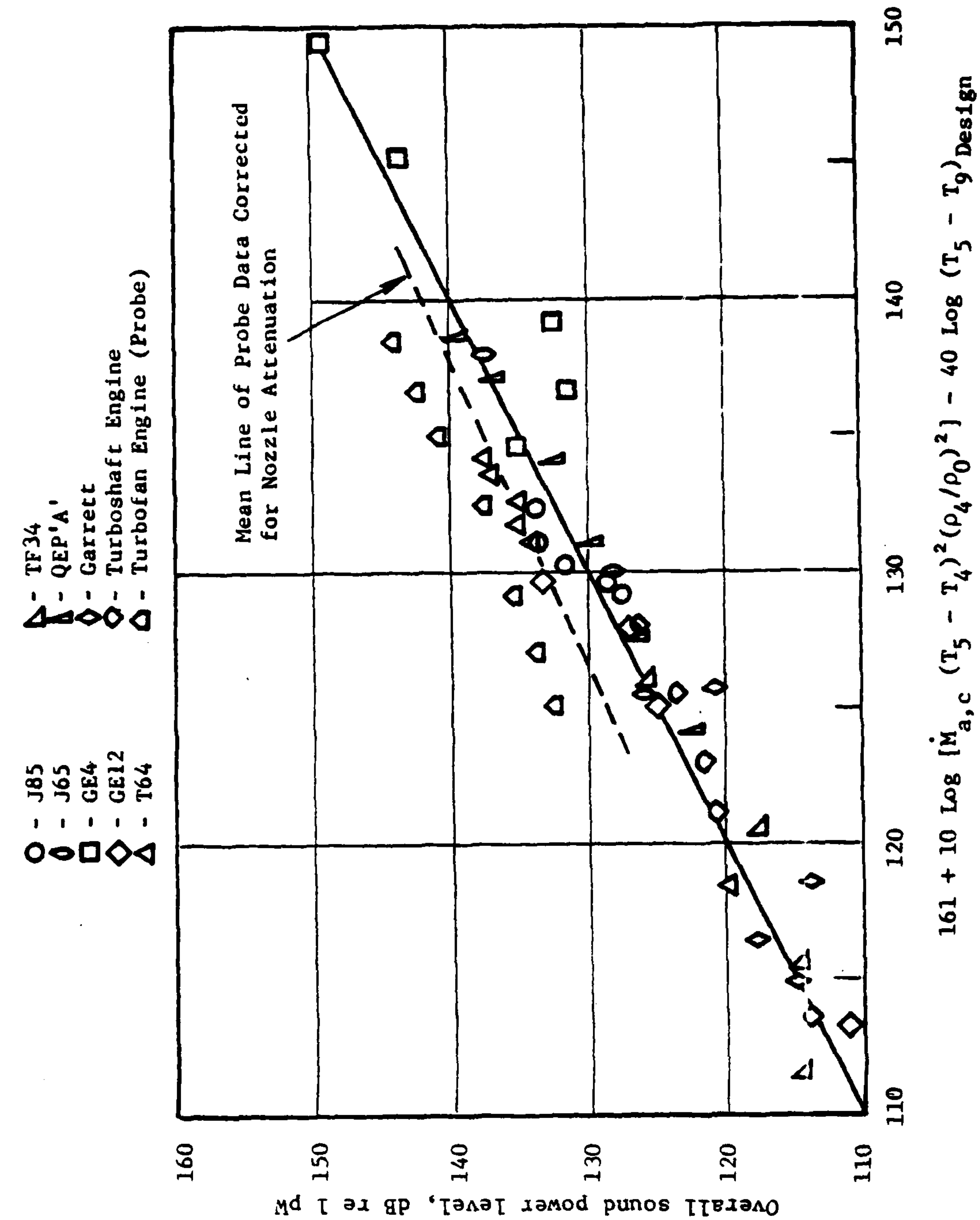


Figure 12. - Overall sound power level correlation for core-engine noise, ref. 18.

at the compressor exit was attenuated in the combustor and lost through the turbine. Two probes were located at the same axial position on the wall of the combustor but 90° apart. One probe was located at the combustor entrance. Cross-correlation analysis showed a strong correlation at a time delay indicative of an acoustic signal traversing the combustor. Acoustic wave propagation was indicated by cross-correlation analysis between probes at the turbine exit and primary nozzle exit and by microphones in the near- and farfield.

Figure 13 shows the 1/3-octave-band pressure spectra obtained at each location. Below 2000 Hz it is seen that there was a 15 dB attenuation in the signal through the turbine. In the farfield the signal was on the order of 50 dB below that at the nozzle exit. Cross-correlation analysis showed that strong correlation between the nozzle exit and farfield signals occurred at a time delay consistent with acoustic propagation. A negative time delay was shown in the cross-correlation of the signals measured at the combustor exit and in the farfield. Earlier work by Karchmer and Roshotko[20] had indicated a 180° phase shift between the combustor-exit and farfield signals and an amplitude change proportional to the square of the frequency indicating that the combustor is in an acoustic source region.

The variation in sound power, calculated from farfield microphone measurements and from pressure measurements at the nozzle exit, as a function of jet velocity is shown in Figure 14. To eliminate contamination from high frequency sources, the sound power was calculated using data between 50 and 2000 Hz only. The results in Figure 14 showed that for low jet velocities (less than 150 m/sec) the sound power level calculated from data measured at the nozzle exit was in good agreement (slightly higher because atmospheric absorption effects were not accounted for) with that in the farfield. Above 150 m/sec the farfield sound power level followed a near eighth-power dependence on jet velocity. It was concluded that at low jet velocities the farfield noise from the YF-102 was indicative of noise emanating from the combustor.

Muthukrishnan and Strahle[21] have used both analytical and experimental techniques to show that entropy or indirect combustion noise may be the

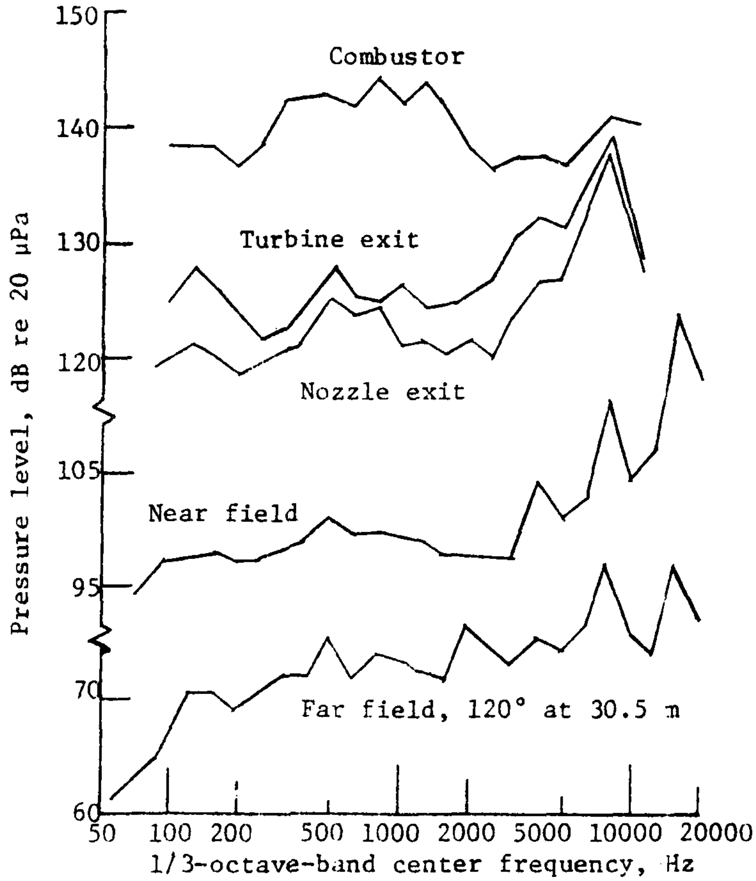


Figure 13. - YF-102 internal and external pressure level spectra; engine speed = 43%, ref. 19.

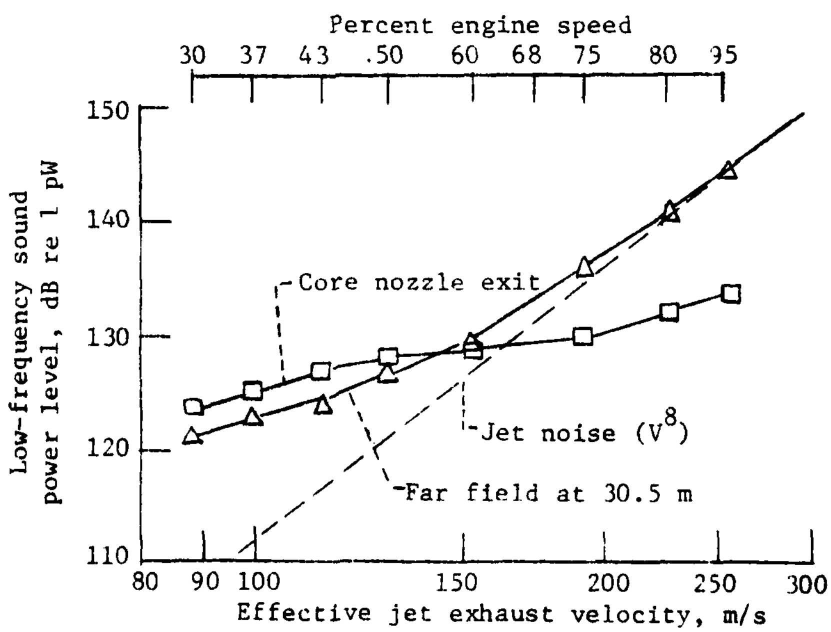


Figure 14. - YF-102 low-frequency sound power level, 50 to 2000 Hz, ref. 19.

prime contributor to internal engine noise under certain flow conditions. Combustor rigs exhausting directly to the atmosphere are free from entropy noise contamination because of the absence of temperature fluctuations propagating through large pressure gradients at the combustor exit.

To generate indirect combustion noise, an exhaust nozzle was positioned on the combustor exit which imposed a pressure gradient on the heat fluctuations during combustor operation. By ordinary and partial coherence techniques it was shown that at low nozzle-exit Mach numbers, the farfield noise levels resulted from direct combustion noise. However, at high nozzle-exit Mach numbers, such as encountered with a turbine operating at choked conditions, indirect combustion noise dominated. Indirect and direct combustion noise were shown to be highly correlated below 100 Hz making it virtually impossible to separate the two sources. Below 150 Hz, there was unexpectedly low coherence between the near- and farfield microphones. Strahle concluded that hydrodynamic noise, which does not propagate, contaminated the near-field signal. By proper placement of the near-field pressure transducer outside the hydrodynamic flow field, the contribution from this source was minimized. Low coherence values above 150 Hz were attributed to an unexplained source of noise which did propagate, possibly vorticity noise.

Roundhill[22] reported on results from an independently-funded joint Boeing/AiResearch program aimed at combustion noise from auxiliary power units. Three combustors were tested: (i) production GTCP-85 combustor, (ii) low-emissions combustor (lean fuel mixture), and (iii) high-altitude combustor (rich fuel mixture). The results of the tests showed that the combustor was the principal source of noise in an auxiliary power unit. Also, reductions in the farfield sound power level on the order of 5 dB were achieved with the low-emission and high-altitude combustors.

For comparison, high- and low-bypass-ratio turbofan and turbo-shaft engine data were correlated with both the P&WA and GE core noise prediction procedures. Both procedures correlated the data within 5 dB with similar directivity and spectrum shapes. Ho of AiResearch[23] reported that the results of the joint Boeing/AiResearch program also showed that a stoichiometric mixture in the combustor produced the most noise. In addition,

noise reductions were achieved by using natural gas or propane instead of JP5 for fuel.

Lowrie and Hopkins[24] of Rolls Royce reported on various results obtained with the RB.211 Quiet Engine Demonstrator (QED) and the Viper turbine rig. The objectives of the tests were to determine if the "excess" noise at low frequencies could be attributed to aerodynamic, combustion, mixing, or interaction sources. Preliminary results showed that large swirl angles onto the QED outlet struts caused low frequency noise. However, minimizing this source still left a significant source attributed to combustion noise in the 100 to 500-Hz frequency range. Cross-correlation analysis between in-duct and farfield transducers confirmed that the combustion process was the principal noise source. Comparison with the Garrett, General Electric, Boeing, and P&WA combustion noise prediction procedures showed that the Rolls Royce data correlated well with the General Electric method.[5,18]

3.2 Presentations at the AIAA 5th Aeroacoustics Conference

Recent advances in combustion noise theory and prediction were presented at the AIAA 5th Aeroacoustics Conference in March 1979 in Seattle, Washington. In general, it was noted that a unified prediction method is still needed to correlate noise data from combustor rigs and engines. Strahle[25] presented a theoretical analysis based on one-dimensional plane-wave motion in which the perturbation pressure and velocity were split into a dilation part due to acoustic wave motion and a vortical part due to turbulence. The results of the analysis showed that the acoustic power has three significant terms (i) heat release fluctuations or direct combustion noise, (ii) entropy or indirect combustion noise, and (iii) vorticity noise. An order of magnitude study showed that all three sources influence the pressure fluctuations in the combustor. The contribution of entropy and vorticity noise mechanisms was found to depend upon the pressure gradient at the combustor termination. In particular, the farfield noise from combustor rigs that exhaust directly to the atmosphere has no contribution from entropy and vorticity noise.

In the absence of entropy and vorticity mechanisms, the theory suggested a scaling law of the following form:

$$L_W = K_{16} + 10 \log [(1/N_f^{a})(A_c^{0.5}/L_c)\, A_e\, V_{axial}^2\, \overline{P}_c]$$

$$+ 10 \log [((T_5 - T_4)/T_4)^2(1/(T_4 + (T_5 - T_4)))] \qquad (16)$$

where $0 \leq a \leq 1$ for lean to rich burning.

Experimental results with a combustor exhausting directly to the atmosphere and one with an acoustical impedance matching device showed that there can be up to a 10 dB difference in radiated sound power. This difference was compared with the difference between the results reported by P&WA[15] of tests using combustors exhausted to the atmosphere (i.e., with an impedance mismatch) and the results reported by General Electric[5,14,16] where the combustor rig was operated with an acoustical termination that was considered reflection free. The difference between the GE and the P&WA data was on the order of 7 dB.

A linear multiple-regression analysis[25] applied to the results of References 15 and 16 with a 7 dB "reflection-free" correction yielded a correlation expression similar to Eq. (16) but with the pressure and velocity terms given by p^2V^4 (using rounded-up exponents) instead of PV^2. The difference in the exponents was attributed to a dynamic head (proportional to ρV^2) and indicated aerodynamic noise contamination in the combustor noise measurements.

Strahle emphasized the need for further work to extend the scaling law by including entropy and vorticity mechanisms in the correlation of engine noise data. In addition, turbine and exhaust-duct attenuation effects were identified as requiring further work.

At the Conference, noise escalation due to the installation of low-emission combustors was the subject of considerable attention. Ho and Doyle[26] of the General Electric Company reported on an update of the GE prediction method[5,14,16] which extended the correlation to include temperature effects due to stage or sectional burning akin to that used in low-emission combustors. At airplane approach-power conditions only the pilot stage of a two-stage double annular combustor would be used. As a result, more of the total

airflow bypasses the combustion region and the higher fuel/air ratio in the combustor results in a higher exit temperature than that for a comparable single-stage combustor. The higher combustor temperature results in higher noise levels.

2.4 Summary

In summary, the low-frequency noise in excess of the extrapolated jet noise levels at low engine power settings is attributed to the combustion process. Three mechanisms of combustion noise have been identified (i) direct combustion noise due to heat fluctuations, (ii) indirect or entropy noise due to the convection of temperature inhomogeneities through downstream pressure gradients, and (iii) vorticity noise due to turbulence interacting with downstream pressure gradients. Direct combustion noise is the dominant source for combustor rigs. However, the importance of entropy and vorticity noise for full scale engines is still not clear.

Based on noise scaling laws, several ways to reduce combustion noise were identified:

1) Increase combustor inlet temperature
2) Reduce combustor inlet pressure
3) Reduce combustor through-flow velocity
4) Reduce fuel/air ratio
5) Increase turbine pressure ratio
6) Increase number of fuel nozzles
7) Stage the burning process
8) Reduce combustor temperature rise

However, a large temperature rise in the combustor and a large temperature drop across the turbine are required for the most-efficient turbine performance. A certain turbulence level and heat release rate per unit volume are also required to satisfy energy, thrust, and fuel consumption requirements. Federal aircraft-engine-emission requirements add to the constraints on combustor design features which limit the prospects for significant combustor noise reduction.

An empirical prediction procedure based on combustor performance and geometry parameters is still needed to correlate both combustor-rig and full-scale-engine noise data. The prediction procedure must incorporate appropriate expressions for the effects of downstream pressure gradients. Such a procedure must also be able to assess the noise produced by low-emission combustor designs with sufficient accuracy so as not to compromise other design constraints of the engine and airframe system.

3. JET NOISE

3.1 Background

Jet noise is generated as a result of the turbulent mixing of the jet exhaust with the ambient air. Lighthill's[27-28] theory of convected quadrupoles with subsequent modifications by Ribner,[29] and Ffowcs-Williams,[30] is the most widely accepted model of jet noise generation. According to the nonconvective aspects of Lighthill's theory the acoustic power radiated by a point quadrupole can be shown to be proportional to the square of the source strength times the fourth power of a characteristic source frequency resulting in an eighth power dependence of the farfield mean squared acoustic pressure on jet velocity. The convective aspects of the Lighthill theory suggested that the mean squared acoustic pressure at a distance R should be modified by a Doppler term to the sixth power:

$$\overline{p^2}_{moving} \sim \overline{p^2}_{static}/(1 + M_c \cos \theta_i)^6 \qquad (17)$$

where $\overline{p^2}$ = mean squared acoustic pressure and the subscripts indicate whether the quadrupole sources are moving or static;

M_c = convection Mach number of the quadrupoles sources (local velocity of turbulent eddies relative to the external jet flow divided by the speed of sound in the ambient air); and

θ_i = far field observer angle relative to the upstream jet exhaust axis.

Ribner and Ffowcs-Williams suggested a fifth power rather than sixth power dependence for the convection effect on Eq. (17) and developed the more general expression which also eliminated the singularity at $\theta_c = \pi - \cos^{-1}(1/M_c)$:

$$\overline{p^2}_{moving} \sim \rho_j^2 V_j^8/[(1 + M_c \cos \theta_i)^2 + \alpha^2 M_c^2]^{5/2} \qquad (18)$$

where ρ_j = jet density;

V_j = jet velocity; and

α = semi-empirical constant.

It is important to note that Eq. (18) represents the overall mean-squared sound pressure; it does not provide any information on the spectral distribution of the jet noise at any angle.

Since jet engine thrust varies as $A_j V_j^2$ while acoustic power varies as $A_j V_j^8$ (A_j = jet exhaust area), jet noise suppression at constant thrust can be achieved by increasing the exhaust area and reducing the exhaust velocity. For turbojet or low-bypass-ratio turbofan engines, some jet noise suppression at constant thrust can be achieved by external mixer nozzles that modify the mixing process downstream of the nozzle exit by entraining additional ambient air to more-rapidly reduce the exhaust velocity. Turbofan engines produce less jet noise than turbojet engines at the same thrust because they have higher mass flow rates with larger exhaust areas and lower exhaust velocities. Suppression of jet noise produced by turbofan engines having co-annular exhaust nozzles is a unique problem because of the weight and performance penalties associated with the use of an external mixer nozzle on the primary exhaust stream. Mechanical noise suppressor devices for high-velocity, high-temperature jets have been the subject of an extensive design and testing program.[31]

Development of jet noise suppression devices for turbojet or turbofan engines has always required extensive static and flight testing. To eliminate the need for extensive tests and to provide a more-rational basis for the design of noise-suppression devices, DOT initiated a jet noise suppressor study in the early 1970s with the General Electric Company. Responsibility for the study was subsequently transferred to the FAA. Some of the major results of the DOT/FAA-funded jet noise suppression study were presented at the February 1977 Conference.

3.2 Review of Jet Noise Presentations at the 1977 DOT/FAA Conference

Under the the DOT/FAA High Velocity Jet Noise Source Location and Reduction Program,[31] GE developed a unified, analytical aerodynamic/acoustic model for predicting the noise characteristics of round-convergent and suppressor nozzles. Analytical models were presented for the mean properties of the flow field, the turbulence in the mixing region of the jet plume, and the shielding of the jet noise by the flow around the jet. A semi-empirical method for the prediction of shock-cell noise adapted from the work of Harper-Bourne and Fisher[32] was also presented. Also dis-

cussed was the generation of jet noise by the flow past the lip of the exhaust nozzle, the effect of the orderly structure of turbulence in the jet stream on noise generation, and particle/fluid injection as a means of reducing jet noise.

The unified prediction technique was verified by comparison with extensive jet noise data from round, convergent nozzles, conventional coannular nozzles, inverted-velocity-profile nozzles, and complex multielement noise-suppressor nozzles over a wide range of operating temperatures and velocities.

The initial efforts to develop an improved jet-noise prediction model involved a significant refinement and extension of an earlier jet-noise prediction method developed by Mani of GE. The earlier model was based on a plug-flow model of the jet stream from a circular jet. The circular-nozzle plug-flow model was extended to make it applicable to noncircular nozzles of arbitrary shape. The purpose of the extension was to help explain the reason for the variation of farfield sound pressure level produced by such nozzles as a function of angle around the jet axis in a plane perpendicular to the jet axis and containing the nozzle exit. When applied to a rectangular nozzle of reasonably high aspect ratio, the extended plug-flow jet noise model was capable of predicting the observation that the sound pressure level in that plane at a point in line with the major axis was less than that at a point in line with the minor axis.

A major consequence of the development of the extended plug-flow jet-noise model was a detailed study of the shielding of the various acoustic point sources of noise within the jet by elements of the jet flow itself, i.e., the so-called fluid-shielding phenomena. The theory predicted that the acoustic intensity at a point in the farfield was proportional to the cross-sectional area of the jet subtended from the point of observation, thus explaining the result noted above for high-aspect-ratio rectangular nozzles.

An experiment was conducted to evaluate jet-flow shielding effects. A model-scale coannular jet was constructed. The duct to the primary nozzle

was arranged so that it could be connected to a siren or to a flow of compressed air. The farfield noise from the siren source was measured with and without the coannular flow surrounding the primary nozzle. With the flow from the secondary nozzle, the noise levels at the fundamental and harmonics of the siren noise were lower than with the flow absent. The noise reduction was greatest at angles close to the jet axis. At a given angle, the noise reduction increased as the velocity of the secondary flow increased.

Similar results were obtained when the siren was replaced by a flow of air from the primary nozzle indicating that fluid shielding was effective in reducing noise from both the siren source and the convected quadrupole sources in the primary jet flow. The tests indicated that there was a net reduction in radiated acoustic power. With the primary-jet-flow noise source, the reductions in farfield noise levels, when the secondary jet flow was turned on, were mainly at shallow angles to the jet axis and at high frequencies for the model-scale jets. The noise reduction increased as the temperature, velocity, and thickness of the annular jet flow were increased.

Although the extended plug-flow jet-noise model did provide some new insight into the effect of fluid shielding on the intensity and directivity of farfield noise from nozzles of arbitrary shape, it was considered to be limited to jets with relatively low exhaust velocities and to relatively low frequency (long wavelength) sound sources. In order to provide a model with a broader range of applicability, GE adopted a new approach that led to the new unified aeroacoustic model for jet noise.

The most-significant feature of the unified aeroacoustic prediction model for jet noise is the expression for the farfield noise levels as a function of the small-scale turbulent eddies whose properties are modified as they are convected along by the surrounding jet flow. The prediction model divides the jet plume into elemental volumes with dimensions characterized by the scale of turbulence at that axial location in the jet, see Fig. 15. Each elemental volume is considered to be independent so that the total farfield noise levels can be obtained by summing the contribution of acoustic power from each element.

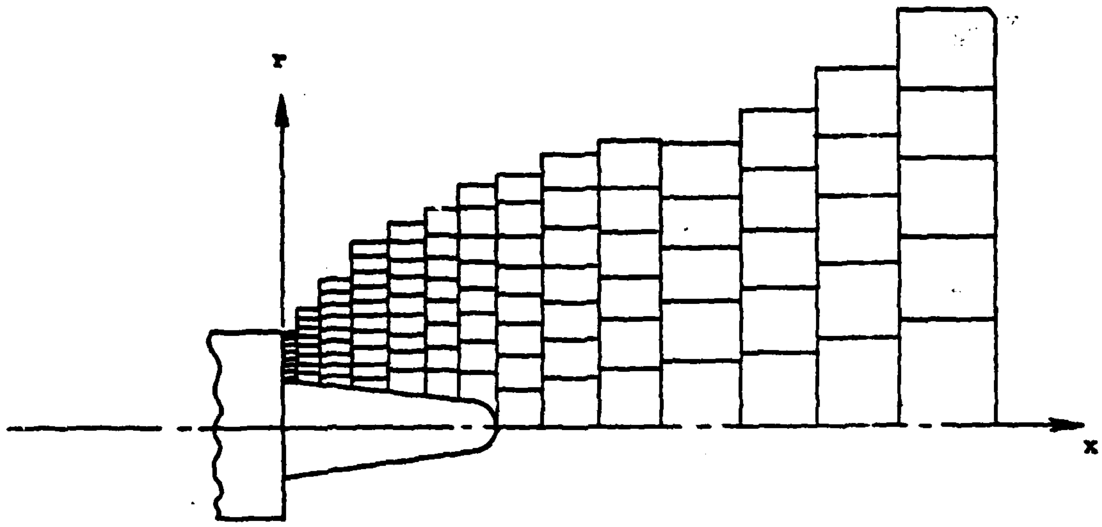


Figure 15. - Typical subdivision of Jet-Plume Flow Field into Eddy Elemental Volumes (not to scale), ref. 31.

The description of the flow field in the jet plume was based on the linear theory of Reichardt[33] for free turbulence. The linearity of Reichardt's theory is an essential feature of the GE prediction model and allows the superposition of flow elements to construct complex flow fields from nozzles of arbitrary cross section. The momentum, enthalpy flux, and shear stresses in the elements of the jet flow are calculated from a contour integral around an arbitrary exit planform using cylindrical coordinates. From those expressions, the axial velocity, density, and turbulence intensity for each element are defined throughout the jet plume. For nozzles with a centerbody, coordinate transformations for the radial and circumferential coordinates are provided to modify the flow field expressions in the region of the centerbody, see Fig. 15.

The farfield noise spectrum produced by the free turbulence in each elemental volume was estimated from Lighthill's[27-28] classical expressions as modified by Ribner.[29] The resultant expressions for the turbulence intensity correspond to Ribner's "self noise" contributions where the scale of turbu-

lence has been further approximated by the mean turbulence velocity and a characteristic time delay for correlation.

The directivity of the farfield noise produced by turbulence intensities in each elemental volume was shown by GE to depend on the amount of shielding by neighboring elemental volumes in the jet stream. Fluid shielding was described as a combination of convection, refraction, and temperature effects. Expressions for the effect of fluid shielding on farfield noise levels were derived by considering the noise produced by stationary point quadrupoles immersed in a parallel shear flow. For a convected point source, it was shown[31] that the sound pressure field depends on a shielding function which is a function of the farfield observation angle and distance r across the jet.

$$G^2(r) = \frac{(1 + M(r)\ \cos\ \theta_i)^2 (c_0(r)/c_a)^{-2} - \cos^2\ \theta_i}{(1 + M_c\ \cos\ \theta_i)^2} . \qquad (19)$$

The consequence of the zeroes of the shielding function is an exponential term that varies depending on the location of the elemental volume radially across the jet. Thus, the number of zeroes for the shielding function determines whether an elemental volume is shielded and the degree of shielding. Extending the theory to convected quadrupoles yielded a similar dependence for the shielding function on the location of the convected point surfaces. Ribner[29] showed that the farfield acoustic pressure is proportional to the pressure fields from the various convected point quadrupoles as

$$\overline{p^2} = \int_y (\Pi)(a_{xx} + 4a_{xy} + 2a_{yy} + 2a_{yz})\ d\vec{y} \qquad (20)$$

where $\Pi = [I(\Omega)/(16\pi^2 R^2 c_a{}^4)](\rho_a/\rho_0)^2\ (c_a/c_0)^2\ (1 + M_0 \cos\ \theta_i)^{-2}\ (1 + M_c\ \cos\ \theta_i)^{-1}$

R = propagation distance

c_a = ambient speed of sound

c_0 = speed of sound in the elemental volume

(ρ_a/ρ_0) = ambient-to-mixing-region density ratio

M_0 = convection Mach number of elemental volume

M_c = eddy convection Mach number

Ω = narrow band frequency

θ_i = angle measured relative to inlet axis

and $I(\Omega) \sim \rho^2\ (u')^7\ (\Omega\ \tau_0)^4\ \exp\ [-(1/8)(\Omega\ \tau_0)^2]$ is a measure of the intensity

of the turbulence where ρ = mean flow density

u' = turbulence velocity

τ_0 = characteristic time delay

and a_{xx}, a_{xy}, a_{yy}, and a_{yz} are directivity factors for each quadrupole type in each elemental volume.

When the shielding function G^2 [from eq. (19)] is positive, all the quadrupoles contribute to the farfield noise level. A negative shielding function results in only an x-x quadrupole contribution with directivity given by a_{xx}. The quadrupole directivity factors are related to the shielding function by complicated expressions, see Ref. 31 for details. The effect of fluid shielding was to cause the maximum high-frequency noise to occur at a high angle relative to the jet axis and the maximum low-frequency noise to occur closer to the axis. The result is a "zone of silence" around the axis for subsonic low-temperature jets.

When the entire jet moves through the air the intensity of the acoustic power in the forward quadrant is increased, and that in the aft quadrant decreased, relative to the intensity calculated for a stationary jet. This "convective amplification" effect results from motion of the acoustic sources in the jet relative to the medium and the observer and is accounted for by multiplying the Π term in Eq. (20), and hence the mean-squared pressure, by $(1 - M_\infty \cos \theta_i)^{-1}$ where M_∞ is the free-stream Mach number. The effect of convective amplification is only to modify the directivity of the jet noise, not the spectrum at any point.

Flight or forward-motion effects were not a major part of the GE study. Development of the unified aeroacoustic jet-noise-prediction model was aimed primarily at predicting the noise of stationary jets. Essentially all of the comparisons between theory and experiment used data measured around stationary jets. To account for forward motion effects would require incorporation of a Doppler shift in the spectrum at a point and a modification to the calculated source strength due to a reduction in the shear forces which is accounted for by using the relative jet velocity $(V_j - V_\infty)$ instead of V_j. The Doppler frequency shift and the relative velocity factor are in addition to the convective amplification factor for directivity described above.

Section 4 presents a more-general discussion of the effects of forward motion on jet and combustion noise.

Two cases of jet noise suppression by physical shielding were examined analytically.[31] The first case considered was that of a sound source in the vicinity of a very long (semi-infinite) barrier that was either a perfect acoustic reflector or a perfect acoustic absorber. The problem addressed in this study is related to the question of jet-noise shielding by airplane fuselage, tail, and wing assemblies. The results of the analysis showed that when the line of sight between the source and observer is just at the barrier edge, a noise reduction of 6 dB is obtained for both the rigid and the absorptive wall. The noise reduction increased as the source-to-wall distance was decreased and as the frequency was increased. The additional noise reduction achieved with the absorptive wall was limited to 6 dB.

The second analytical study addressed the question of how much noise reduction could be expected from placing a shroud around the initial part of the jet flow. The problem was modeled by treating the shroud as a two-dimensional pair of semi-infinite parallel plates with an embedded line singularity. An important result of the study was the finding that the strength of a quadrupole source can be enhanced by interaction effects at the trailing edge of the shroud unless the source is embedded deeply within the shroud close to the nozzle exit. An ejector around the jet was studied as a practical version of a shroud. Unless the ejector was longer than 1.5 to 2 nozzle exit diameters, the shielding of the acoustic quadrupole sources provided by the walls of the ejector was effective only for high frequencies (high Strouhal numbers) and at large angles to the jet axis. The main benefit of the ejector was augmentation of the mass flow and hence thrust under static conditions (or for very low aircraft Mach numbers), rather than enhanced reduction of jet noise.

The expressions in Eq. (20) were developed for noise generated by subsonic jets where $M_j = V_j/c_j$ is less than 1.0 and the nozzle exit pressure ratio is less than the critical pressure ratio. For nozzles operating at high supercritical pressure ratios, the farfield jet noise is dominated by shock noise. Shock formations divide the jet plume into cells, see Fig. 16.

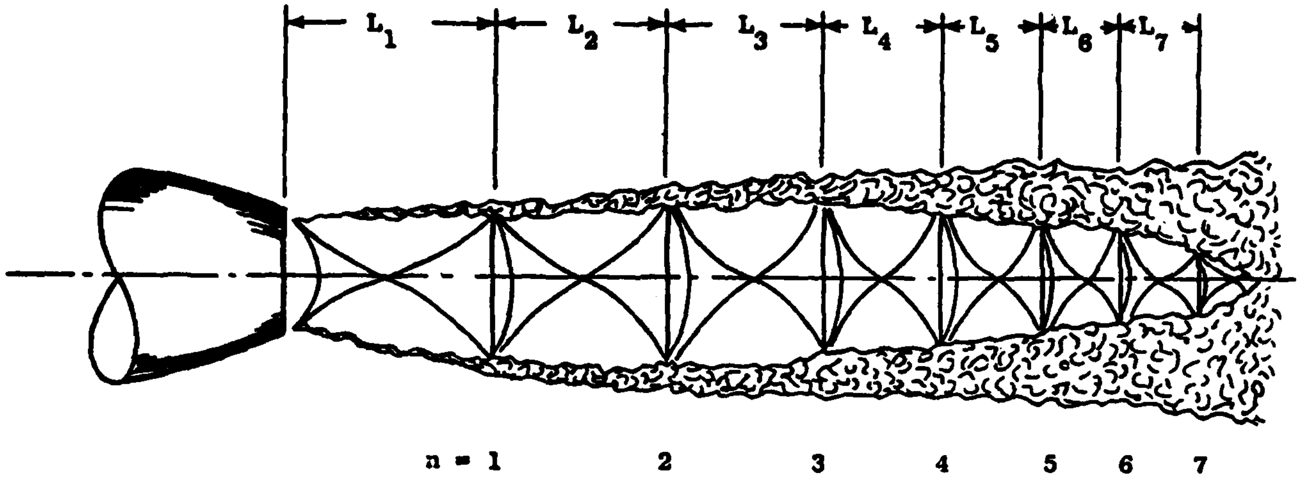


Figure 16. - Schematic representation of n shock cells of length L_n in an underexpanded supersonic jet operated at a nozzle pressure ratio above the critical pressure ratio, ref. 31.

Turbulent eddies, which convect downstream, pass through and disrupt the shocks thus generating shock noise. A broadband spectrum is generated due to the random nature of the turbulent eddies. This broadband spectrum is modified by interference effects caused by cancellation and reinforcement between acoustic waves propagated from adjacent shock cells. The shock noise prediction model developed by GE was a modification of the Harper-Bourne and Fisher[32] method. Modifications were made to extend the methods to nozzles of arbitrary cross section. Comparisons of the shock-noise theory for circular jets with measurements of the noise produced by non-circular jets suggested that the difference between the predictions and the measurements could be accounted for by differences in the structure of the shock cells in the jet. The modifications to the theory included expressions for the number of cells, cell spacing, and shock angle.

Shock strength is computed from

$$\beta^2 = M_j^{\,2} - 1 \tag{21}$$

where $M_j^2 = [2/(\gamma - 1)][PR^{(\gamma -1)/\gamma} - 1]$ is the square of the jet Mach number, γ is the ratio of specific heats, and PR is the nozzle exit pressure ratio. If the shock angle, ϕ, is known then M_j^2 should be replaced by $M_j^2 \sin^2 \phi$.

Average shock-cell spacing scales with an equivalent diameter, D_{eq}, as

$$L_{avg} = 1.1 \; \beta \; D_{eq} \tag{22}$$

where $D_{eq}^2 = 4A_j/\pi$ and

A_j = total flow area at the nozzle exit.

Peak frequency of the shock-noise spectrum was given as

$$f_p = (V_c/L_{avg})(1 + M_c \cos \theta_i)^{-1} \tag{23}$$

where $V_c = 0.7 \; V_j$ is the convection velocity of the turbulent eddies,

$M_c = V_c/c_a$, and

θ_i = far field directivity angle measured from the upstream jet axis.

The sound pressure level (SPL) spectrum at angle θ_i and distance R is computed from

$$\begin{aligned} SPL = {} & 152.6 + 40 \log_{10} (\beta) + 10 \log_{10} (A_j/R^2) \\ & + 10 \log_{10} (D_h/D_{eq}) - 40 \log_{10} (1 - M_\infty \cos \theta_i) \\ & + 10 \log_{10} (N/8) - 10 \log_{10} (f/f_p)^e \end{aligned} \tag{24}$$

where D_h = hydraulic diameter, $4A_j/P_w$,

P_w = wetted perimeter,

M_∞ = flight Mach number,

N = number of shock cells, and

e = a constant with the value of 1.0 when $f > f_p$ and the value -7.0 when $f < f_p$.

Noise produced by turbulent eddies passing by the lip of an exhaust nozzle was studied experimentally. The contribution of lip noise to the total jet noise level was found to be negligible.

The effects of large-scale orderly structures in the turbulent flow field of a subsonic jet were studied analytically by Ribner as a consultant

to GE. From theoretical considerations and tests conducted by GE involving two-point velocity correlations, Ribner[34] concluded that, while large-scale structures do exist and do contribute to the development of turbulence, they have little effect on noise.

Injection of particles or fluids of various kinds into the jet flow had been proposed by several investigators as a means to reduce jet noise. Injection of large quantities of water, for example, was known to be able to achieve some noise reduction. GE studied the concept of fluid/particle injection and found no significant noise reduction for hot jets with any practical system.

Reporting on some results of work conducted under contract to the NASA Lewis Research Center, Packman, et al.,[35] of Pratt & Whitney Aircraft described the noise reduction benefits of duct-burning turbofan engines. This special type of turbofan engine is characterized by an inverted velocity profile; i.e., the bypass or fan secondary exhaust velocity is greater, rather than less, than that of the primary flow. The high fan-exhaust velocity is achieved by burning fuel in the fan duct to increase the energy and raise the speed of sound in the flow. The result is increased thrust at the same inlet mass flow rate at the expense of increased fuel consumption and other costs. The duct-burning turbofan is a candidate engine for an advanced supersonic transport.

Farfield noise levels were measured around two scale-model coannular nozzles with fan-to-primary exit-area ratios of .75 and 1.2. Tests were conducted over a wide range of fan and primary exhaust velocities. Noise from the coannular nozzle was compared with that from a single-stream nozzle operated at jet velocities equal to the fan and primary velocities from the coannular nozzle. The results showed that the sound power level of an inverted-velocity-profile jet was less than the sum of the sound power levels from a single-stream jet at the corresponding fan and primary velocities.

Measurements of temperature and velocity profiles in the coannular jet provided an explanation for the noise reduction. The flow characteristics of the inverted-velocity-profile jet are such that the mixing region

between the fan-exhaust flow and the ambient air contains the most-intense noise sources. The inverted-velocity-profile jet, however, exhibits a more-rapid velocity decay than does a single-stream jet operating at the same fan-exhaust velocity. The more-rapid velocity decay reduces the strength of the sources of jet noise at frequencies associated with low-to-mid Strouhal numbers.

For a given area ratio, the acoustic power produced by the inverted-velocity-profile jet decreased as the ratio of the fan-exhaust velocity to the primary-exhaust velocity was increased. The rate of decrease was negligible above a velocity ratio of about 2.

In a long-duct common-flow-exhaust-nozzle arrangement for the inverted-flow system, it was found that installation of a forced-mixing nozzle, instead of a round-convergent nozzle as the internal primary nozzle, did not yield any significant noise suppression. The failure of an internal mixer nozzle to achieve any noise reduction with the inverted-velocity-profile system contrasts with the benefits provided by using an internal mixer on the primary for a conventional turbofan where the primary velocity is greater than the fan or secondary velocity.

Installation of a forced-mixing nozzle on the turbine-discharge duct in the long-duct common-flow exhaust systems on JT8D and JT8D-refan engines reduced the overall sound power at the same thrust. The internal mixer nozzle in such an installation achieves a partial inversion of the flow within the tailpipe by forcing some of the hot, high-velocity flow outward and inducing some of the cooler, lower-velocity flow in toward the axis. The result is a reduction of the average jet exhaust velocity at the exit.

Stone[36] of the NASA Lewis Research Center reported on experimental results for the noise generated by coannular inverted-velocity-profile jets with and without a centerbody plug, see Fig. 17.

Noise levels produced by the inverted-profile coannular jets were compared with the noise produced by a synthesized equivalent single-stream jet. The synthesized jet noise was obtained by summing the mean-squared

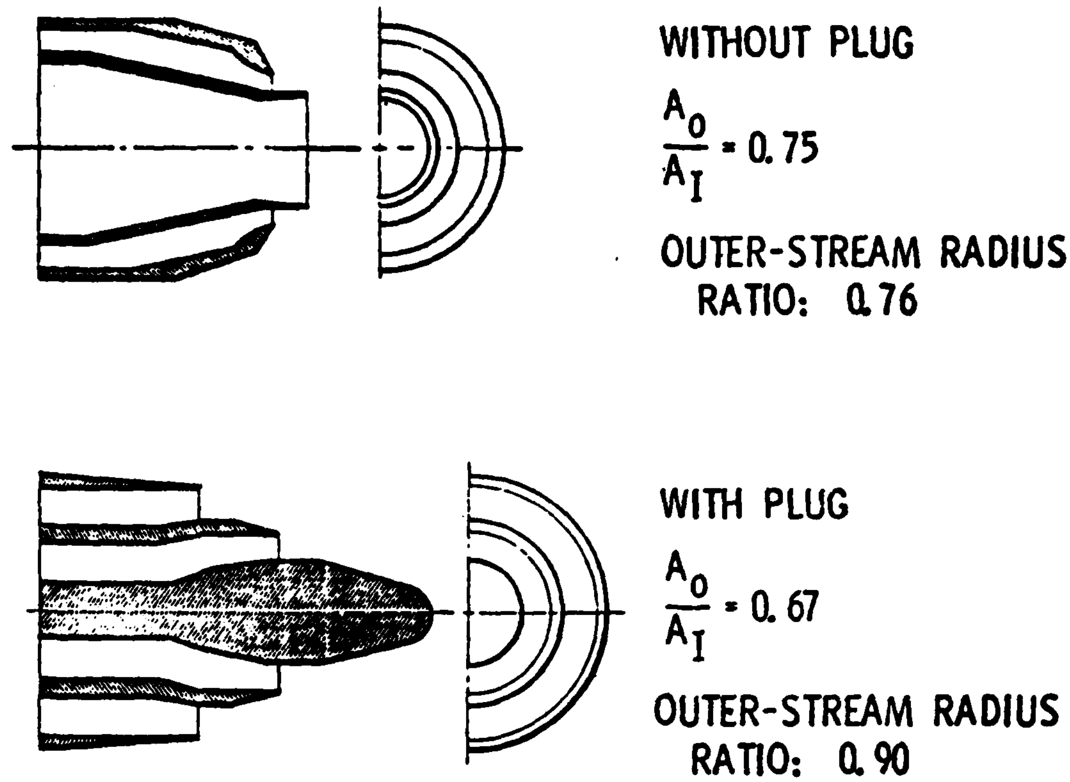


Figure 17. - Inverted-velocity-profile coannular model nozzles, ref. 36.

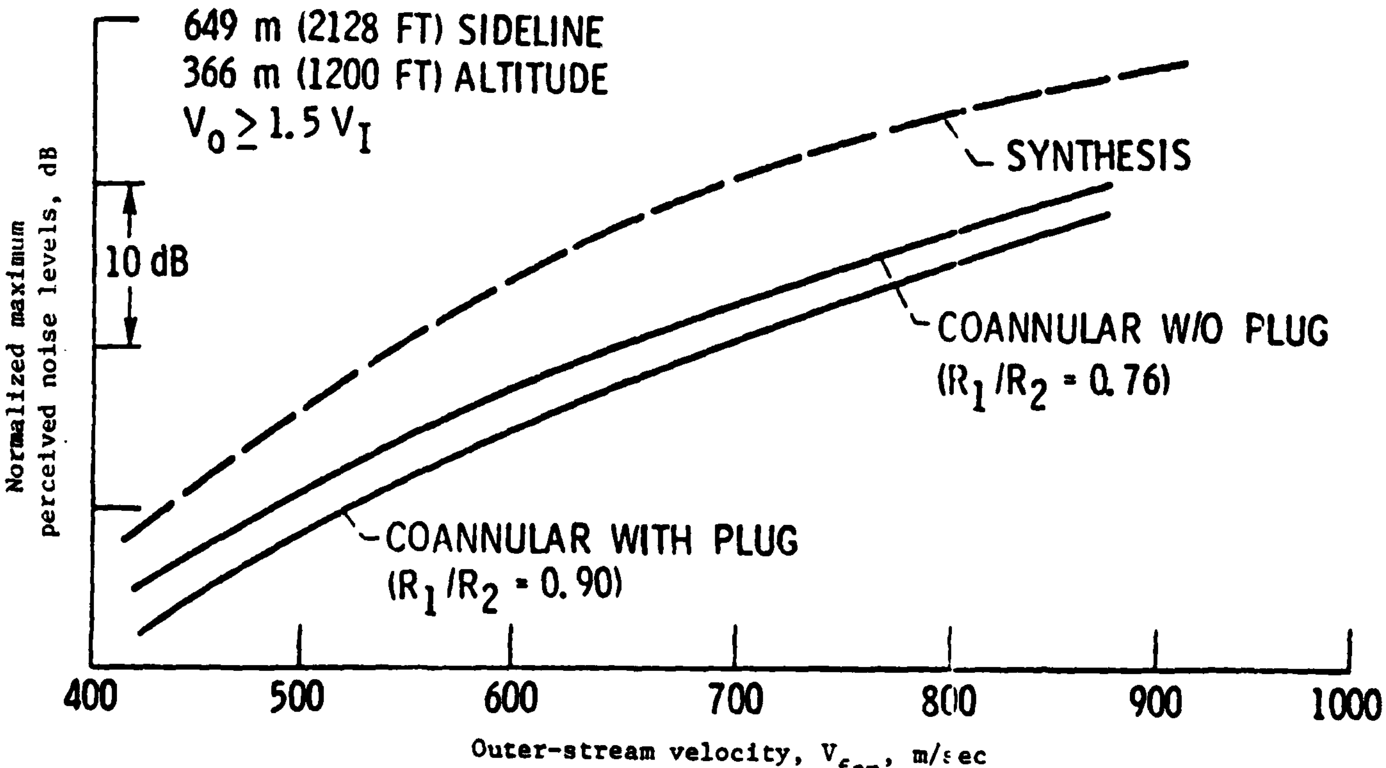


Figure 18. - Maximum sideline perceived noise level for inverted-profile coannular nozzles and synthesized equivalent single-stream jet, ref. 36.

farfield sound pressures generated by two round-convergent nozzles having the exit areas of the inner and outer jets from the coannular nozzles and operated at the same jet-exhaust velocities.

Figure 18 shows normalized maximum perceived noise level on a 649-m sideline as a function of the outer stream, V_0 or V_{fan}, jet velocity for the two inverted-velocity-profile coannular nozzles as well as for the synthesized equivalent single-stream jet. The coannular nozzle without centerbody plug was 7 to 8 dB quieter than the synthesized jet. The coannular nozzle with plug was about 2 dB quieter than the coannular nozzle without the exhaust plug.

Figure 19 shows noise suppression data relative to the noise level of the synthesized single-stream jet for the plug-nozzle coannular jet at two different nozzle-exit area ratios and an outer-stream jet velocity of 700 m/sec. The minimum noise occurred at an inner-to-outer-stream velocity ratio of 0.5. This result agrees with that reported by Packman of P&WA. For a constant outer-stream jet velocity, the noise increased as the inner-stream velocity was made less than half that of the outer stream.

Figure 20 shows data for a fixed velocity ratio of 0.5. Noise was reduced as the radius ratio of the outer stream at the nozzle exit was reduced — i.e., opening the nozzle by making R_2 larger for fixed R_1 or by making R_1 smaller for fixed R_2 and increasing the outer stream mass flow rate to preserve the velocity ratio. The velocity coefficient (thrust), however, also decreased as the radius ratio was increased.

3.3 Presentations at the AIAA 5th Aeroacoustics Conference

As with combustion noise in the previous Section, the major presentations of new results from jet noise research and development studies subsequent to those presented at the February 1977 DOT/FAA Conference were given at the 5th AIAA Aeroacoustics Conference in Seattle, Washington in March 1979. Most of the jet noise papers at the 5th Aeroacoustics Conference were related to the problem of explaining the effects of flight on jet-noise generation. These papers are discussed in the next Section.

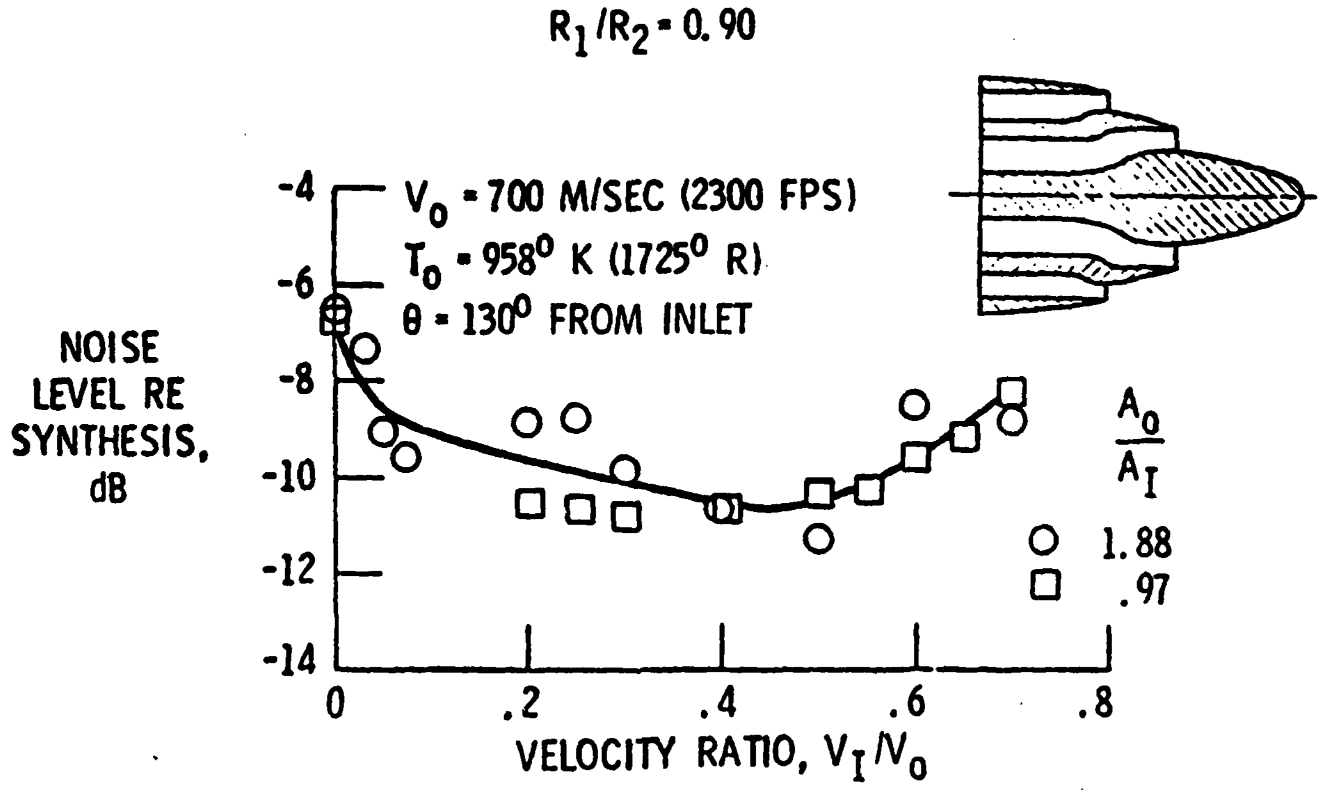


Figure 19. - Effect of inner-to-outer-stream velocity ratio on noise suppression for inverted-velocity-profile coannular nozzles, ref. 36.

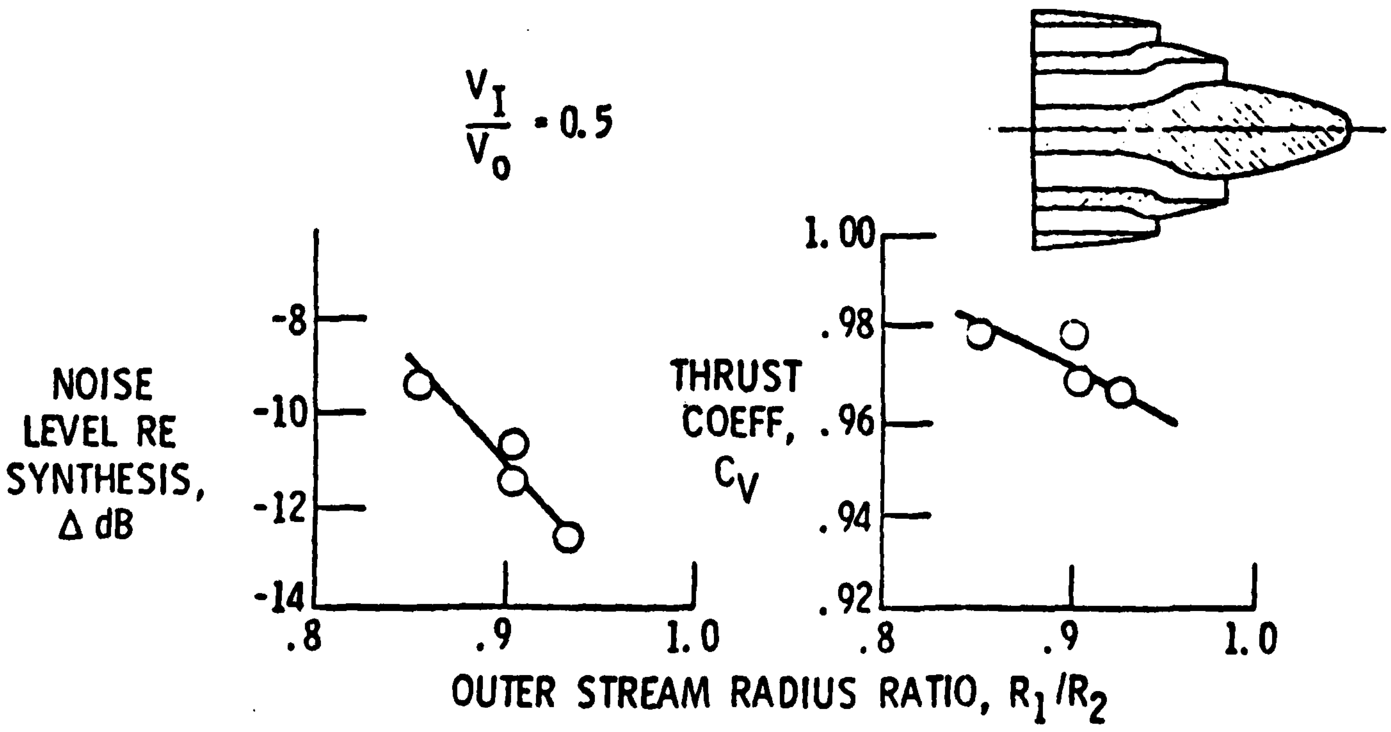


Figure 20. - Effect of outer-stream nozzle-exit radius ratio on noise suppression and thrust for inverted-velocity-profile coannular nozzles, ref. 36.

Papers were presented at the Conference that were related to improvements in understanding of jet noise generation. Several papers described developments in the use of laser/Doppler systems to study the structure of the turbulent flow field in the jet exhaust. B. J. Tester of Lockheed-Georgia and C. H. Berman of The Boeing Commercial Airplane Co. described analyses and experiments that were concerned with models for the turbulent flow field and the generation of jet noise by turbulent mixing processes.

The principal discussion of jet-noise research which was a direct extension of a presentation at the February 1977 DOT/FAA Conference was that in a paper given by James R. Stone, Jack H. Goodykoontz, and Orlando A. Gutierrez of the NASA Lewis Research Center.[37] In that paper, the authors presented results of additional experiments and analyses of inverted-velocity-profile coaxial-jets as part of the NASA investigations of concepts for propulsion systems that might be used by an advanced supersonic jet transport in order to meet stringent aircraft-noise-certification requirements for takeoff and sideline noise levels.

As noted in the presentations made by Packman[35] and Stone[36] at the February 1977 DOT/FAA Conference, the inverted-velocity-profile jet from a duct-burning turbofan engine can produce significantly lower noise than a single-stream jet from an equivalent turbojet engine of the same cruise thrust. The lower noise level is thus achieved with much less weight, performance, and cost penalty than would accompany the use of some type of mechanical jet-noise-suppressor nozzle on the equivalent turbojet engine.

The paper by Stone, et al. presented experimental data from an extensive series of tests of inverted-velocity-profile coaxial jets of various geometries and operated over a range of conditions. Three coplanar and one non-coplanar jets were tested.

Far field sound pressure level measurements at multiple sideline distances were used to infer locations for sources of jet noise at various frequencies within the jet flow field. Pressures and temperatures were measured throughout the flow field. The results were used to refine the jet-noise prediction model developed by Stone and his colleagues at NASA Lewis and improve its accuracy at high frequencies.

Noise generated by inverted-velocity-profile jets was modeled as the combined contribution from four independent and uncorrelated noise source regions and noise generating mechanisms as indicated in Figure 21. The noise sources consist of

(1) a mixing region between the merged jet and the ambient air (subscript m);

(2) a mixing region between the premerged jet and the ambient air (subscript p);

(3) interaction effects between shocks and turbulence in the inner jet flow (subscript s, 1); and

(4) interaction effects between shocks and turbulence in the outer jet flow (subscript s, 2).

The empirical correlations needed to develop the jet-noise prediction model were formulated for the coaxial jets so that they approached the correlations for the single-stream jet in the limit as the velocities and temperatures of the two streams approached equality. Noise from the merged jet is relatively low in frequency and was modeled as the contribution from a circular jet at equivalent merged conditions and total exhaust area. Noise from the premerged region is higher in frequency and was modeled as the contribution of an equivalent plug nozzle at outer stream conditions with the low frequencies attenuated since the outer jet from coaxial nozzles is relatively thin and the typical turbulence length scale is relatively small compared with that in the merged jet. Noise from shock/turbulence interactions was modeled using a NASA modification of the model of Harper-Bourne and Fisher.[32]

The two important aspects of the paper were the determination of the apparent sources of noise in the premerged and merged regions of the jet flow field and the measurement of the flow properties within the jet exhaust plume. Knowledge of the flow properties is needed for the jet-noise prediction model and assessment of the capability to predict the flow properties was important.

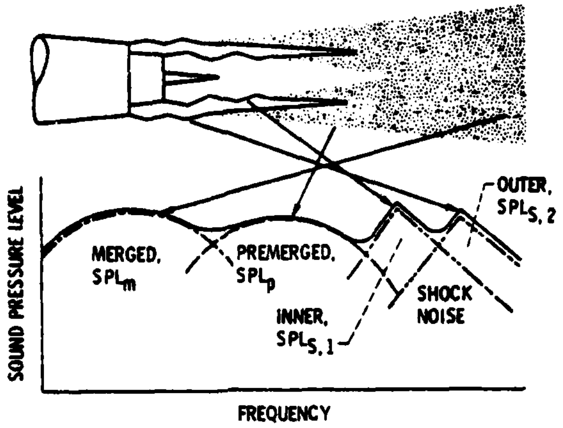


Figure 21. - Conceptual illustration of source of jet noise in an inverted-velocity-profile jet, ref. 37.

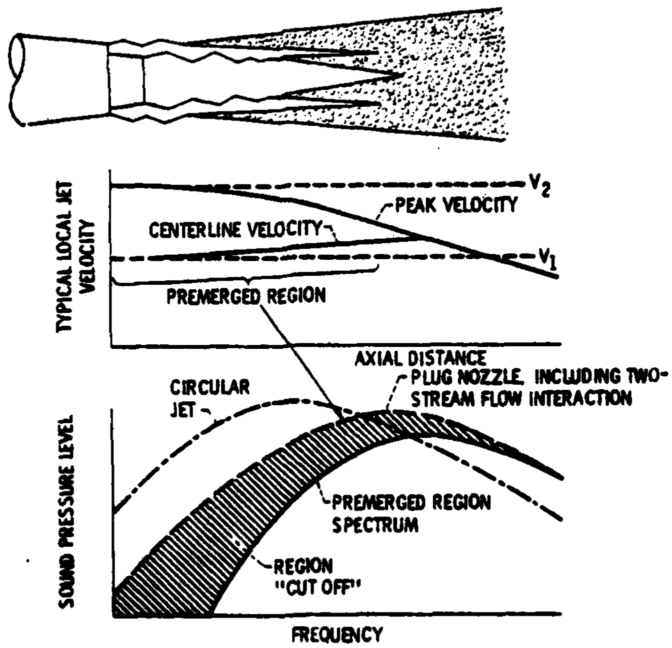


Figure 22. - Illustration of axial variation of local jet velocities and model of high-frequency jet noise spectrum from pre-merged region of inverted-velocity-profile jet, ref. 37.

Total and static pressure and total temperature were measured throughout the jet plume. Local flow Mach numbers were calculated from the pressure data. Static temperatures were calculated from the total temperatures and local flow Mach numbers. Velocities were calculated from the Mach numbers and the local speed of sound determined from the static temperatures.

Local maximum and centerline jet velocities were determined for all the inverted-velocity-profile test nozzles. The maximum velocity, which is initially in the outer-stream region, decreases rapidly with axial distance while the centerline velocity increases slightly in the premerged flow region. The length of the premerged region increased with increasing nozzle-exit area ratio and hence increasing flow in the outer stream.

At some distance downstream, the centerline velocity reaches a maximum and then decreases. Figure 22 shows the general trends in local jet velocities that were confirmed by the experimental results. The frequency spectrum of the noise modeled by the pre-merged part of inverted-profile jet is also shown in Figure 22. Prediction equations for the level and spectrum of the sound pressure were developed and validated for the noise produced by the various test nozzles and for nozzles previously tested.

3.4 Summary

Research conducted by the General Electric Company under the DOT/FAA high-velocity jet-noise program significantly improved the understanding of the mechanisms of jet-noise generation. The research also advanced the ability to predict farfield noise levels generated by the turbulent flow field from the wide variety of exhaust-nozzle geometries that might be considered for mechanical devices to reduce the jet noise produced during takeoff of an advanced supersonic jet transport. The analytical and experimental tools developed under the program should be useful not only in designing jet-noise-suppressor concepts, but also in helping to reduce engineering development costs.

The DOT/FAA High-Velocity Jet Noise Source Location and Reduction Program was conducted in five major tasks. Presentations at the February 1977

Conference were concerned with results from Tasks 2 and 4. Task 4 was concerned with techniques for simulating and evaluating flight effects on jet noise generation, radiation, and suppression and is reviewed in the next Section. The most-significant achievement of Task 2 was the development and successful validation through exhaustive series of experiments of a new procedure for predicting the level, spectrum, and directivity of jet noise in the far field.

The unified aeroacoustic jet-noise prediction method developed by the General Electric Company has three main components: (1) prediction of the mean aerodynamic properties of the flow field in the exhaust from subsonic and supersonic jets from nozzles of arbitrary shape, (2) descripion of the turbulence properties of the jet exhaust that are relevant to jet-noise generation, and (3) prediction of farfield noise on the basis of the mean flow properties and the characteristics of the convected turbulence and including the effects of shielding of the convected acoustic sources in the jet flow by elements of the flow itself. Noise caused by shocks in the exhaust of jets operating above the critical (sonic) nozzle pressure ratio was modeled by a semi-empirical extension of a theoretical model.

The other jet-noise presentations at the Conference were related to suppression of the jet noise produced by candidate engines for an advanced supersonic jet transport and to suppression of jet noise produced by turbofan engines for subsonic jet transports.

A promising alternative to a turbojet engine, or a variable-cycle turbofan/turbojet engine, for an advanced supersonic jet transport is a low-bypass-ratio turbofan engine with fuel burned in the fan-discharge duct as well as in the primary combustion zone. Duct burning would be used for high-thrust operations such as takeoff and supersonic cruise. The profile of the exhaust velocities from a duct-burning turbofan is inverted in the sense that, in contrast to a conventional turbofan engine, the secondary or fan-exhaust velocity is greater than the primary or turbine-exhaust velocity.

Measurements of the noise produced by models of inverted-velocity-profile coaxial jets (both coplanar and non-coplanar) demonstrated that the jet noise

produced by such an arrangement is several decibels less than that produced by an equivalent single-stream jet producing the same thrust. Empirical models were developed to predict the local velocities in the jet exhaust and the spectrum and directivity of the farfield noise levels for various exhaust-nozzle geometries and flow conditions.

Special nozzles installed on the turbine-exhaust duct within a long-duct common-flow exhaust nozzle can improve the cruise performance and reduce the jet noise at takeoff power for low-to-medium-bypass-ratio turbofan engines. These special nozzles reduce the average jet velocity at the nozzle exit by forcing some of the primary and secondary flows to mix within the tailpipe. The concept of an internal forced-mixer nozzle may also be useful for reducing jet noise from high-bypass-ratio turbofan engines if means can be developed to reduce the weight and performance penalties associated with long-duct nacelles made from metal.

4. EFFECTS OF FLIGHT ON JET-MIXING NOISE AND COMBUSTION NOISE

4.1 Background

The reduction of jet-mixing noise in flight by a jet-noise-suppresor nozzle has been demonstrated several times to be less than that predicted on the basis of projecting measurements around a static engine test stand to equivalent flight conditions. That result was seen during the development of the forced-mixing jet-noise-suppresor exhaust nozzles for the turbojet-powered DC-8 and 707 airplanes in the late 1950s. Smaller noise reductions in flight than predicted from static noise measurements were also observed during the FAA-sponsored study of a jet noise suppresor for the 727 airplane in the early 1970s.[38] For that program, the jet-noise suppressor consisted of a 20-lobe forced-mixing nozzle in combination with an acoustically-lined ejector.

A similar result was also observed during development of the Concorde supersonic jet transport. On the basis of static tests and analyses, an exhaust nozzle was developed that contained devices which extended into the hot jet stream during takeoff and then retracted for cruise. These devices were later eliminated from production Concordes after flight tests indicated that the noise reduction was less than predicted. Some jet noise suppression at points below the takeoff flight path is achieved on production Concordes by partially closing the buckets of the thrust reversers during climbout after liftoff.

In addition to the differences between predictions and flight-test measurements from these and other examples of efforts to develop jet noise suppressors, there was an area of some controversy in the early 1970s, which persists to the date of this report in 1979, relative to the effect of forward motion on the noise produced by a jet exhausting from a round convergent nozzle.

From theoretical considerations, Ffowcs-Williams[30], Ribner[29,39],

and others had shown that jet-mixing noise from subsonic jets issuing from a round nozzle should be lower in flight than measured statically by a factor proportional to the logarithm of a power of the ratio of the static jet velocity to the relative in-flight exhaust jet velocity. When a jet moves through the air, the rate of mixing with the ambient air is reduced because the shear gradient at the boundary is reduced, the length of the potential core is increased, the effective acoustic source volume is reduced, and, hence, the acoustic strength of the jet noise should be reduced. At any angle, the calculated reduction should apply equally over the range of frequencies covered by a jet-noise spectrum. The exponent of the velocity ratio was calculated to vary with directivity angle and jet velocity, but some noise reduction at every angle was expected on the basis of the theory. Changes in the convective effects of the jet flow and the noise sources within the jet were calculated to cause the noise reductions in flight to be greater in the downstream direction (rear arc) than in the upstream direction (forward arc). There would, however, always be noise reductions and no noise amplification.

In contrast with the theory, experimental data available in the late 1960s and early 1970s, however, had indicated that static, low-frequency engine noise levels projected to flight conditions were higher at angles in the forward quadrant than actual flyover noise measurements from aircraft powered by jet engines having round exhaust nozzles. Noise levels were lower at angles in the aft quadrant, as predicted.

On the basis of this experience with the effects of forward motion on jet-noise and jet noise suppressors, a task was included in the GE High-Velocity Jet Noise Source Location and Reduction Program to investigate the effects of forward motion on the jet-mixing noise produced by round nozzles and jet-noise suppressor nozzles. The results of this important task were one of the major items of discussion at the February 1977 Conference. Forward-motion effects on engine-component noise sources have continued to be a significant area of aeroacoustics research. Additional advances subsequent to the Conference are also discussed this Section.

4.2 Review of Flight-Effects Presentations at the 1977 DOT/FAA Conference

4.2.1 *General Electric Company*

Under Task 4 the DOT/FAA High-Velocity Jet Noise Source Location and Reduction Program,[40] GE conducted in-depth reviews of the capabilities of "fixed-frame" and "moving-frame" facilities that could be used to simulate the effects of flight on the generation and suppression of jet noise. A fixed-frame system is one in which the jet nozzle is stationary relative to an observer or microphone. A moving-frame system is one in which the jet nozzle is in motion relative to an observer just as in an actual flyover noise test.

Twelve fixed-frame and four moving-frame facilities were evaluated on the basis of acoustical and aerodynamic requirements as well as availability and modification costs. The twelve fixed-frame facilities consisted of five closed-circuit wind tunnels (two at NASA-Ames, one at NASA-Lewis, one at NASA-Langley, and one at FluiDyne) and seven free-jet facilities (one at the David Taylor Naval Ship Research and Development Center (DTNSRDC), two at the Massachusetts Institute of Technology, one at the United Technologies Corporation Research Center (UTRC), one at NASA-Lewis, one at NASA-Langley and one at General Electric in Evendale, Ohio.

Moving-frame test facilities consist of rocket-propelled sleds on rails, high-speed trains, and spinning rigs. Spinning rigs had been developed several years ago by Pratt & Whitney Aircraft and Rolls Royce. Spinning rigs, however, were not included in the GE survey. (See Refs. 41 and 42 for discussions of the Rolls Royce spinning rig.)

Two rocket-sled facilities were evaluated: one at Holloman Air Force Base near Alamogordo, New Mexico and one at the Naval Weapons Center near China Lake, California. After extensive evaluation, both rocket-sled facilities were rejected for testing of forward-motion effects on jet noise because of the cost of required modifications, the cost and lengthy duration

of a test, and the remoteness of the test sites.

Two high-speed-train facilities were evaluated: one was the DOT Linear-Induction-Motor Research Vehicle at DOT's High-Speed Ground Test Center near Pueblo, Colorado; the other was the Bertin Aerotrain developed by the French aircraft engine company SNECMA and located near Goemetz, France.

The Linear-Induction-Motor Research Vehicle was rejected because of high background noise level at probable microphone locations and because the maximum vehicle speed was significantly less than desired. The Aerotrain was not considered an ideal facility because (1) the test hardware would have to be sized for the nozzle of the J-85 engine used to propel the Aerotrain along the track and thus scale-model test hardware could not be used, (2) the engine cycle conditions that could be investigated were only those of the J-85 engine and hence parametric variations in relevant acoustic and aerodynamic quantities could not be performed, and (3) the maximum vehicle speed was significantly less than desired. The Aerotrain, however, was used by GE for validation tests of a moving-frame test system because jet noise suppressor hardware sized for a J-85 engine was available and because development of the Aerotrain vehicle was well advanced.

Thus, except for some validation testing, moving-frame test facilities were eliminated from the program. Evaluation of the fixed-frame test facilities was based on acoustical and aerodynamic criteria. Of the five wind tunnels, the 7x10-ft tunnel at NASA-Ames came closest to meeting all the criteria: it was deficient, however, in the mass flow rate that could be supplied to a model nozzle and in the fact that testing at elevated jet temperature for a long period of time would not have been possible without extensive modifications. The other four wind tunnels were eliminated because they could not meet the acoustic or aerodynamic requirements without impractical modifications. Free-jet, fixed-frame test facilities therefore were the only ones that were deemed capable of potentially meeting the acoustical and aerodynamic requirements.

The DTNSRDC facility was not designed to have the capability for jet noise testing. The MIT wind-tunnel facilities had no jet nozzle test capa-

bility and the velocities for the free-jet flow were less than desired. The free-jet facility at NASA-Lewis did have a small test section with a model jet, but no capability for testing heated jets. The UTRC facility was in the process of being modified at the time of the evaluation in late 1973 but the planned jet nozzle size was less than desired. Thus, after detailed evaluation, the survey of flight-simulation facilities was reduced to just the Aircraft Noise Reduction Laboratory (ANRL) at NASA-Langley and a modification of an existing facility at GE. The ANRL facility was eliminated because of the limited mass flow rate available for the model jet nozzle and because there was no provision, without extensive modifications, for heating the flow from the model jet. Thus, the GE Anechoic Jet Noise Test Facility was selected as being best able to satisfy all requirements of the program.

Figure 23 shows a schematic cross section of the free-jet fixed-frame jet-noise test facility constructed at the GE plant in Evendale, Ohio. The facility consists essentially of modifications to an existing vertical, concrete cylinder. The cylinder was lined on the inside with wedges made from high-density fiberglass. The wedges provide an anechoic environment at frequencies above 250 Hz. Airflow for the model jet is supplied by two compressed air systems for tests of coannular jet nozzles. A tertiary supply furnishes the air for the large-diameter free jet around the model nozzle. Additional air to make up for the aspiration effect of the jets is admitted through spaces between the wedges at the base of the cylindrical test chamber. Microphones are located as shown in the essentially quiescent, anechoic space.

A free-jet test facility, such as the GE facility in Fig. 23, only partially simulates the effect of motion on jet noise. Although the medium around the exhaust from the model jet is moving at simulated aircraft speeds, the microphones are outside the boundary of the free jet. Sound from the jet-noise sources has to propagate through the free jet, across the free-jet boundary, and then through the still atmosphere to the microphone. Thus an important part of the medium through which the sound propagates is in motion while the microphones are stationary as is the nozzle of the model jet. The flight case, of course, has stationary microphones immersed in a stationary medium through which a jet engine moves at flight velocity.

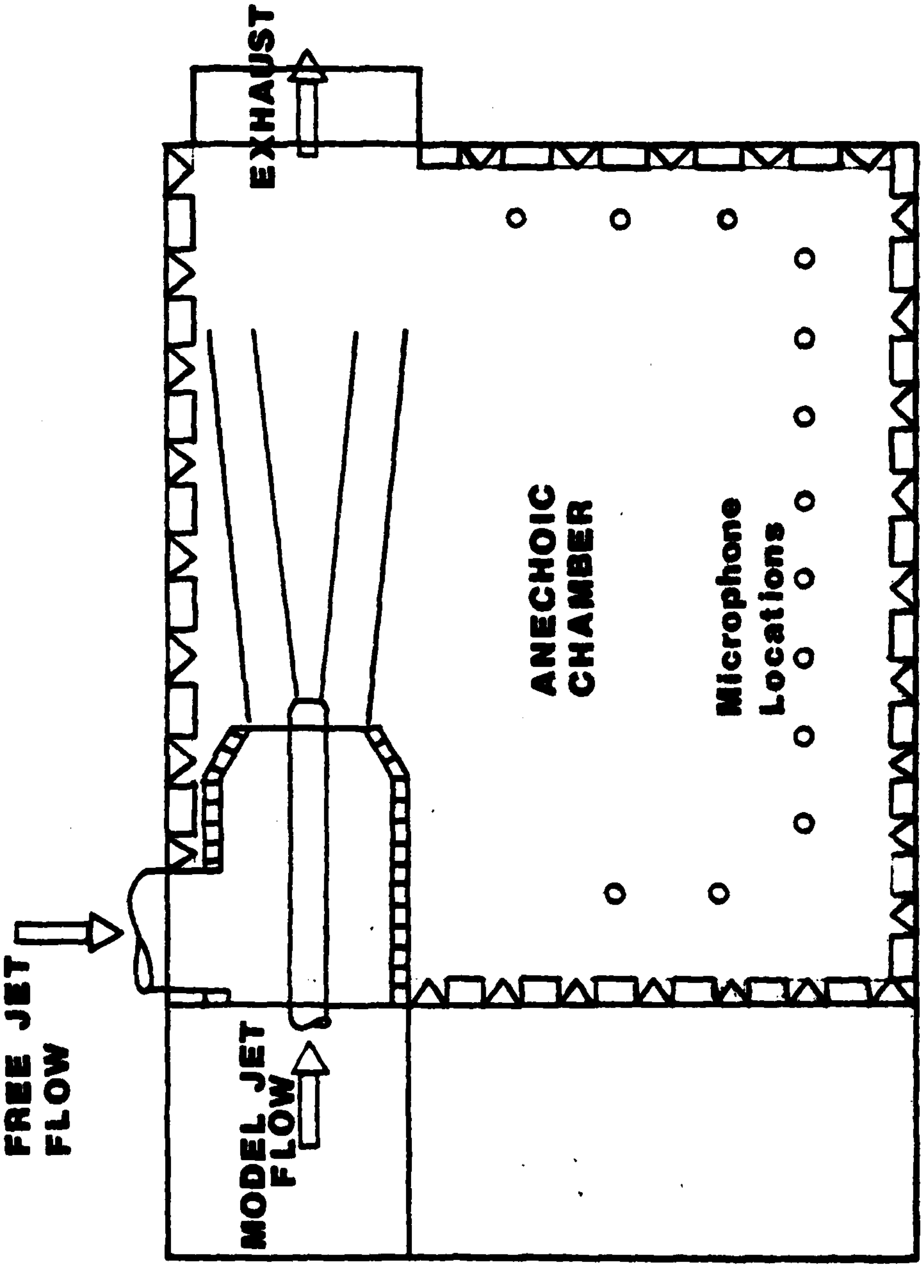


Figure 23.-Schematic of GE free-jet test facility, ref. 40.

To overcome the deficiency in the capability of a fixed-frame, free-jet facility to properly simulate forward-motion effects on jet noise, GE used a theoretical approach to develop an analytical method to transform noise measurements in their free-jet test facility to equivalent flyover noise measurements of jet noise. The process of applying an analytical transformation to free-jet test data was termed the hybrid technique of simulating forward-motion effects. Validation of the hybrid technique was performed by comparing estimated flyover noise levels produced by three types of exhaust nozzles with data for the same nozzles from actual flyover noise tests and with data obtained from tests using the Bertin Aerotrain as a moving-frame test facility. The three types of nozzles were (1) a round, convergent nozzle, and (2) a relatively-simple-geometry version of a jet-noise suppressor nozzle, and (3) a complex-geometry version of a jet-noise suppressor nozzle.

For the sound pressure levels in each 1/3-octave band, the analytical transformation method extracts the basic directivity of the jet noise produced by a model jet nozzle in the GE free-jet test facility. By basic directivity is meant the directivity that would have been measured in a completely static test with no tertiary airflow and hence no free jet flowing around the model jet nozzle, Extraction of the basic directivity data is accomplished by removing the estimated effects of refraction on the sound waves propagating through the free-jet flow and of absorption by turbulence as the sound waves cross the outer boundary of the free jet.

The extended GE plug-flow-model solution[31] for a point source of sound in a jet is used to determine refraction and absorption effects at low frequencies. For high frequencies in the forward, or inlet, arc, the asymptotic, high-frequency solution for an acoustic pressure source is used to remove the refractive effect of the free-jet flow, namely a factor of $(1 + M \cos \theta_i)^{-1}$ for sound pressure, where θ_i is the far-field sound directivity angle measured from the inlet or upstream direction. For high frequencies in the aft, or exhaust, arc, refraction effects are removed by calculating a correction which is the product of a magnitude factor and a shape factor. The magnitude factor is a function of the nondimensional ka product where k is the circular wavenumber $2\pi/\lambda$ and λ is the wavelength at the center frequency of a 1/3-octave band and a is the distance between

the location of a sound source in the jet and a microphone. The magnitude factor specifies the refraction effect on the jet axis ($\theta_i = 180°$). For a given jet Mach number, the magnitude factor increases in proportion to ka for $3 < ka < 6$ and is constant for $ka \geq 6$ at a value which is proportional to jet Mach number. The empirically derived shape factor, which is essentially independent of frequency and jet Mach number is used to modify the magnitude factor determined at 180° and thereby to provide the refraction correction for directivity angles between 90° and 160°. This procedure of using a magnitude and shape factor was derived from studies conducted by Schubert.[43]

For $ka > 30$ (i.e., high frequencies), sound waves traversing the shear layer in the outer boundary of the free jet can lose significant acoustic energy due to interactions with fine-grained turbulence in the shear layer. A theory developed by Crow[44] is used in the GE flight transformation method to develop a correction factor at $\theta_i = 90°$ which is proportional to the product of ka and the square of the jet Mach number. Variation of the turbulence absorption factor (as it is called) with directivity angle, for angles between 40° and 160°, was developed from assumptions for the lengths of the sound paths within the shear layer.

After refraction and turbulence absorption effects have been removed from the data measured in the free-jet facility, the directivity of the basic noise data is matched by the sound radiation field produced by a combination of uncorrelated acoustic point sources. The sources are of various order or singularity level, i.e., monopoles, radial and axial dipoles, quadrupoles and octopoles having a variety of orientations. Separate synthesis procedures are performed for the inlet and exhaust arcs.

For each 1/3-octave band, a special least-squares procedure is used to force the synthesized directivity to fit the "measured" basic directivity pattern (after correcting for refraction and turbulence absorption effects) with an average tolerance of $\pm$ 2 dB over the range of angles. The result is that the directivity pattern is synthesized or reconstituted using a combination of the lowest-order acoustic singularity types which permit matching theoretical and measured directivity patterns with a maximum difference of 3.5 dB.

After an appropriate arrangement of acoustic singularities is defined, an appropriate dynamic effect resulting from convection is applied to each source term. Finally, the spectrum at each far field angle is shifted by a Doppler factor to give an equivalent flight spectrum. For large distances, the flight-transformation program includes an inverse-square distance factor and atmospheric-absorption losses.

A User's Manual describing this analytical transformation procedure is available in Ref. 45.

Verification and validation of the flight-simulation capability of the free-jet facility and the analytical transformation method were obtained by testing the same exhaust nozzle shapes in the fixed-frame facility, on the Bertin Aerotrain moving-frame facility, and on a Gates Learjet and on an F-106 airplane. The results showed good agreement and indicated the usefulness of the hybrid approach. There was, however, some disagreement expressed during the conference on techniques used to account for the contribution of low-frequency noise sources within the J-85 engines on the Aerotrain and F-106.

4.2.2 *Boeing Commercial Airplane Company*

J. P. Roundhill of the Boeing Commercial Airplane Company reported on the results of another approach to simulating forward motion effects on engine noise. Boeing used the 40 by 80-ft wind tunnel at NASA Ames Research Center. A JT8D-17 engine provided by Pratt & Whitney Aircraft was installed in the tunnel and sound pressure levels were measured in the near field along a line parallel to, and 3-m from, the engine axis. Special techniques were used to reduce the noise caused by air flowing over the microphones. Background tunnel noise partially limited the frequency range of valid data. The reverberant character of the interior of the wind tunnel was reduced by installing a 2-in.-thick layer of fiberglass on a large part of the floor and part way up the sides of the test section for a total treated area of about 3000 sq ft.

Three nozzles were tested that had also been tested on an engine test stand and had been flight tested on a Boeing 727. The nozzles were a round, convergent baseline nozzle, a forced-mixing nozzle mounted on the turbine-

exhaust flange as an internal mixer of the primary and fan-duct flows inside a round-convergent external nozzle, and a 20-lobe external mixer nozzle in combination with an acoustically lined ejector. The 20-lobe mixer/ejector nozzle was developed by Boeing for an FAA-sponsored jet-noise-suppresor program.[46] The internal mixer was part of an independent Boeing research program. Test results are given in Refs. 46-48.

For all tests, fan and compressor noise propagating forward from the inlet duct was reduced by installation of acoustically absorptive linings on the wall of the inlet duct and on two concentric rings within the inlet and upstream of the inlet guide vanes. Fan, compressor, and turbine noise propagating aft was reduced by acoustically absorptive linings on the walls of the fan and turbine-discharge ducts.

To relate the near-field, in-tunnel noise measurements to those measured in the far field around an engine test stand, Boeing and NASA-Ames developed a procedure for locating the effective sources of jet noise on the axis of the jet as a function of frequency and jet velocity for the various nozzles. The procedure consists essentially of measuring sound pressure levels along multiple sidelines at various distances from the engine centerline, when the engine is mounted on an engine test stand, and then relating the sideline directivity patterns in the near and far field. The 3-m sideline data from the wind tunnel tests, with the wind on and off, provided a flight-effects correction factor which was added to the sideline data measured around the test stand.

Coordinates for all microphone locations were defined in the usual way by a radius from the center of the nozzle exit and an angle measured with respect to the engine centerline with a vertex at the center of the nozzle exit. This convention does not pose a problem for noise sources that have an effective location near the nozzle exit. Low- and mid-frequency jet noise sources, however, have effective locations which can be several nozzle diameters downstream of the nozzle exit. For these noise sources, Boeing used the multiple sideline data to develop an angular-coordinate transformation between near-field and far-field angle for each 1/3-octave-band center frequency from 50 to 10,000 Hz. Transformations were developed over a wide range of nozzle pressure ratios for

each of the three exhaust nozzles.

An example of the transformation process is shown in Fig. 24. The difference of 14.4 dB between the maximum sound pressure levels could be accounted for, approximately, by an inverse-square-loss correction (+ 20 dB) plus the difference in the correction to the free-field level (- 5 dB) plus an atmospheric absorption correction (less than + 0.1 dB). Assuming that the sound which produced the maximum level on the 30.5-m far-field sideline traveled along a straight line from the effective location of the source, then the location of the maximum 3-m near field sideline was considered to be at the same equivalent 135° angle (measured from the upstream direction) as the location of the maximum on the far field sideline.

Equivalent locations of other angles along the near field sideline were then determined by assuming that the approximately 14-dB difference in the maximum levels would be preserved at all angles. The process of locating the equivalent 70° angle on the near field sideline is illustrated in Fig. 24.

The measured flight effect at a given angle along the 3-m near field sideline in the wind tunnel (i.e., the difference in band level measured with the wind on and off for a given nozzle condition) was then applied to the sound pressure levels at the equivalent angle (for that frequency band, nozzle type, and nozzle pressure ratio) on the far field sideline. The adjusted far field sideline data were projected to the flight condition for comparison with actual flight-test data. Good agreement was indicated.

The wind-tunnel tests corroborated the importance of including flight effects in evaluation of the acoustical performance of jet noise suppressors. Figure 25 shows comparison of the variation of perceived noise level with angle for a level-flight flyover at a height of 122 m. Figure 25(a) shows measurements extrapolated from static data to the flight condition. The flight data in Figure 25(b) were estimated by subtracting static-to-flight effects, derived from the wind-tunnel tests, from the static data in Figure 25(a). The noise suppression achieved by the internal mixer is seen to increase slightly in flight. The noise suppression achieved by the 20-lobe mixer/ejector is much less in flight than would have been determined on the

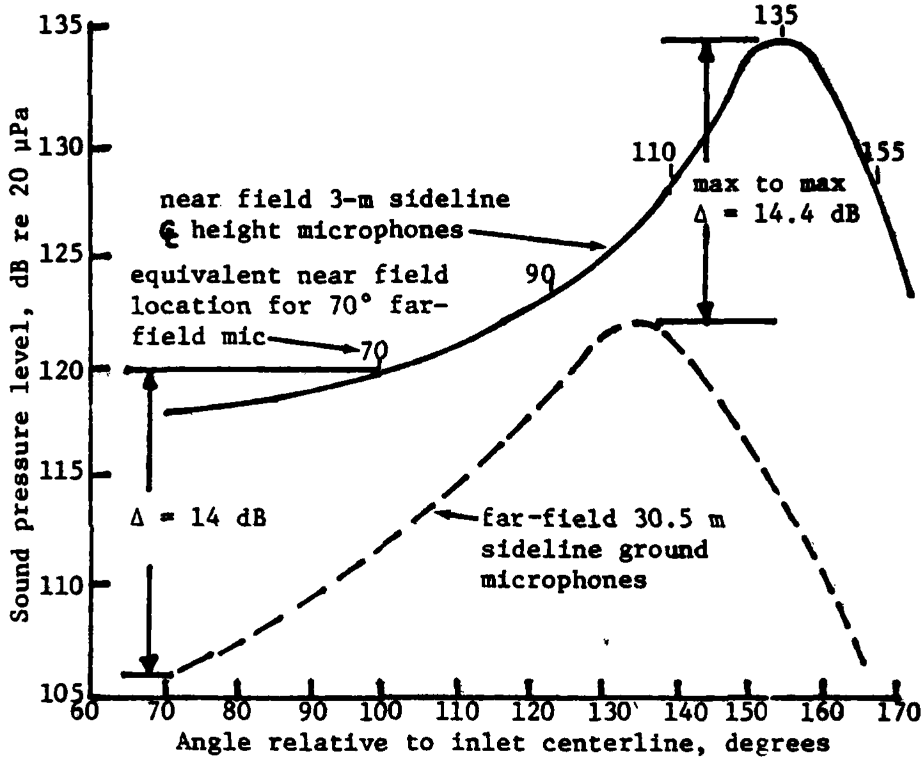


Figure 24.-Typical variation of near- and far-field sound pressure level along sidelines for the 1/3-octave band at 400 Hz for the baseline JT8D-17 at a nozzle pressure ratio of 2.1, ref.46.

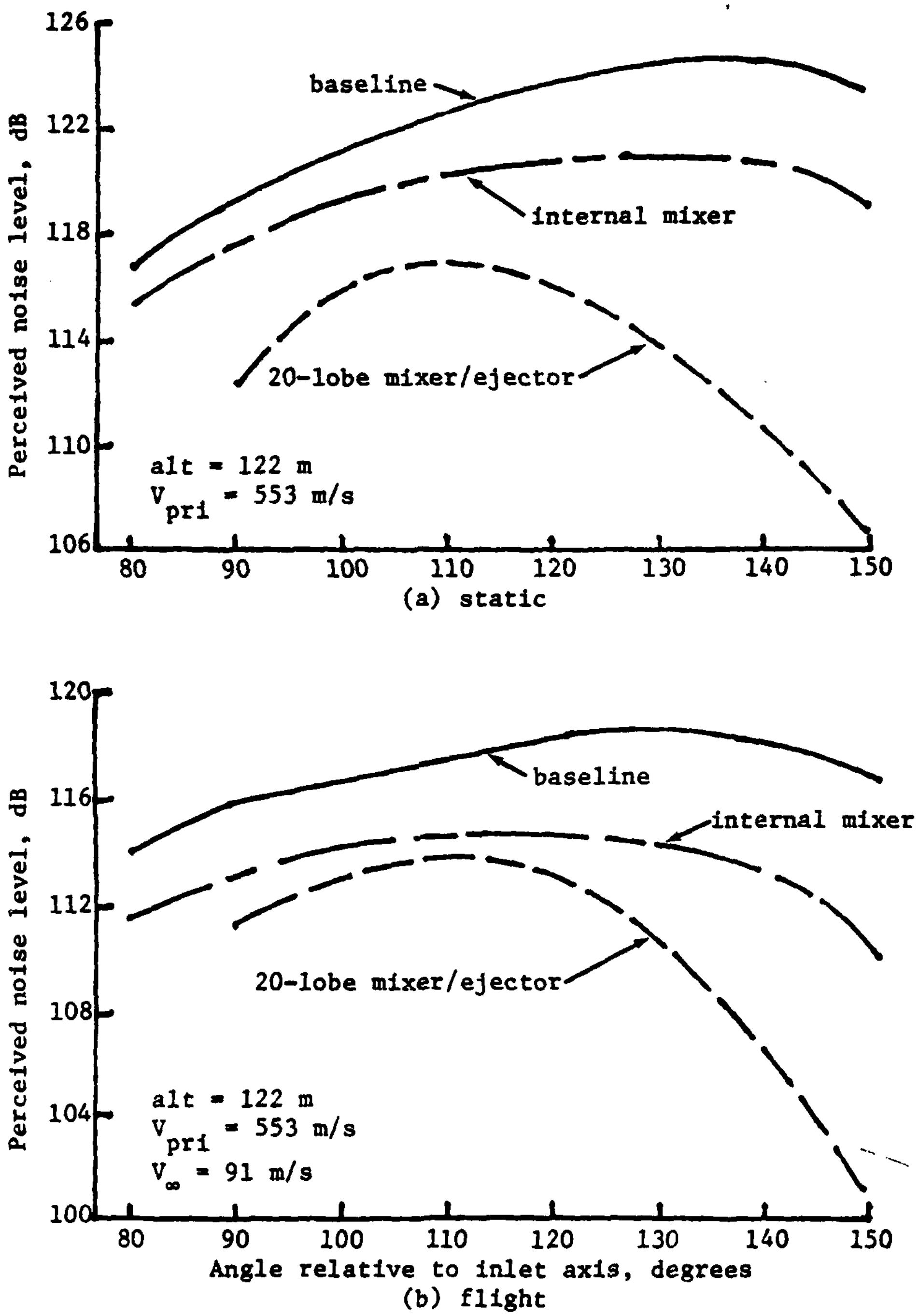


Figure 25.-JT8D engine perceived-noise-level directivity, ref. 46.

basis of static data, a result which was also noted during the full-scale FAA jet-noise suppressor program.[38,46]

4.2.3 *National Gas Turbine Establishment*

Research studies on the effects of forward motion on jet noise had been conducted at the National Gas Turbine Establishment (NGTE) at Pyestock in England since 1973.[42] Initial experiments were done in the test section of a 24-ft-diameter, open-throat, low-speed wind tunnel. The wind tunnel was abandoned in 1975 for studies of forward-motion effects because of problems with tunnel background noise, limitations on the flight speeds that could be simulated, limitations on the range of angular coordinates that could be covered, reflections that degraded the acoustic field within the test section, and limitations on the use of heated jets.

Subsequent to 1975, forward-motion research at NGTE was conducted with a fixed-frame, free-jet facility within an anechoic room. The general arrangement for the new facility is similar to the GE and UTRC[49] free-jet acoustic test facilities. Research was also conducted by NGTE in cooperation with Rolls Royce using their spinning-rig flight simulator. B. J. Cocking of NGTE produced a general prediction method for single-stream and coaxial jets.[50]

R. A. Pinker and W. D. Bryce[51] presented results of using the 1976/1977 free-jet test rig. A loudspeaker, mounted within an upstream plenum chamber for the primary jet flow, was used to simulate an internal, upstream, engine noise source. Sinusoidal signals at 1000 and 2500 Hz were used in order to be able to generate measurable signal-to-noise ratios. (Sufficient acoustic power was not available to generate a measurable signal using a broadband sound.)

At the test frequencies, the sound waves propagating through the 48-mm-diameter jet supply pipe to the 25-mm-diameter jet nozzle were effectively plane waves. Plane waves were considered a reasonable simulation of the low-frequency internal engine noise sources which would probably propagate out the nozzle as plane waves. Jet temperatures to 830 K were tested in the NGTE model

test rig.

The effect of forward motion on the simulated internal noise was that there was little change in amplitude at an angle of 90° to the jet axis. Tone levels were reduced in the rear arc and increased in the forward arc by the simulated forward motion. The effect of flight at various angles was predicted by an expression of the form $10 \log (1 - M_\infty \cos \theta_i)^{-6}$. It was noted that, from theoretical considerations, James R. Stone[52] of NASA Lewis had obtained an exponent of -4, instead of -6, for the factor which is sometimes called a convective-amplification factor or dynamic effect.

4.2.4 *NASA Lewis Research Center*

In developing the NASA Aircraft Noise Prediction Program (ANOPP), the task of providing a method of predicting jet noise and the effects of flight on jet noise had been assigned to the NASA Lewis Research Center, and to James R. Stone in particular.[53] NASA Lewis personnel had been involved with jet noise research since the late 1950s. NASA Lewis had also sponsored engine-development studies, combustion-noise studies, and inverted-velocity-profile studies. In support of the Supersonic Cruise Aircraft Research (SCAR) program, NASA Lewis had conducted and sponsored research on jet noise and flight effects. This background provided a data base for the development of the NASA jet-noise prediction method.

As an effort for the SAE A-21 Committee on Aircraft Noise, a method was proposed in 1976 by personnel from Rolls Royce and SNECMA to account for the effects of flight on the noise produced by single-stream turbojet engines. That method relied on the use of an exponent called m as a function of directivity angle θ_i. The variation of m with θ_i was considered to be unique and independent of jet velocity except at positions in the rear arc ($\theta_i > 130°$).

The basis for the exponent m method was the difference between suitably adjusted flight effects and flight effects predicted from the Ffowcs Williams modification of Lighthill's theory of jet noise generation. Only wideband sound pressure levels were considered because the effect of forward motion on

the amplitude of any spectral component of jet-mixing noise was assumed to be the same as the change in the wideband sound pressure level encompassing all frequencies covered by the analysis.

Values of m were derived from flyover noise measurements and static noise measurements projected to flight conditions. Thus, the empirical variation of m as a function of θ_i was found from measured data using

$$10m \log (V_j/V_{rel}) = L_{WB,\theta_i,S} - L_{WB,\theta,F} - 10 \log [1 - M_\infty \cos (\theta_i + \beta)] \quad (25)$$

where V_{rel} is the relative jet velocity $(V_j - V_\infty)$; V_j is the fully expanded isentropic jet velocity; V_∞ is the velocity of the airplane; $L_{WB,\theta_i,S}$ and $L_{WB,\theta_i,F}$ are the wideband sound pressure levels, at equal directivity angles and distances, that are projected from static measurements and measured in flight, respectively; M_∞ is the free stream or aircraft Mach number, V_∞/c_0; θ_i is the sound directivity angle relative to the upstream jet axis; and β is the angle between the jet axis and the aircraft's flight path on the assumption that the observer is directly below the flight path.

The $10 \log [1 - M_\infty \cos (\theta_i + \beta)]$ term in Eq. (25) is included to account for the so-called kinematic effect, Δ_K, resulting from the relative motion of the airplane with respect to a stationary observer.

Since the exponent m method is intended to be a procedure for predicting the effect of forward motion on jet mixing noise, it is imperative that any suspected contributions from noise sources other than jet mixing be removed from the measured wideband static and flight levels, $L_{WB,\theta_i,S}$ and $L_{WB,\theta_i,F}$. Values of m had been studied empirically by investigators at the engine companies[54-58] and at NGTE[59,60]. A study of flight effects on jet-mixing noise was also performed for NASA by investigators at Lockheed-Georgia[61].

At the Conference, Stone showed that the proposed exponent m prediction curves were rather critically sensitive to the procedures and assumptions made in removing the contributions of non-jet-mixing noise sources from the total measured noise signal, particularly the contribution of internal engine noise

sources such as combustion noise. The most-serious difficulty, in Stone's opinion, was the estimate of internal noise radiated from the J-85 engine statically and from tests using the Bertin Aerotrain. Aerotrain data were one of the primary sources used by GE to validate their analytical flight-transformation method.

Stone presented an alternate approach which was based on theoretical considerations of Ffowcs Williams[30] and Goldstein and Howes[62]. The method included three factors to account for (1) the effect of forward motion on the reduction of the acoustic strength of the noise sources within the jet as a result of the reduction in the shear gradient across the jet boundary under flight conditions or a source-strength alteration effect Δ_{SO}, (2) the effects of forward motion on the ratio of the average axial speed or convection velocity of the turbulent eddies within a jet to the relative jet velocity or the so-called dynamic effect Δ_D on the directivity of the jet-mixing noise, see Eq. (18) and Ref. 63, and (3) the effect of forward motion on the noise level as a result of the relative motion between a translating jet and a stationary observer or the kinematic effect Δ_K described earlier in the discussion of Eq. (25).

At the Conference, Stone presented results from his analysis. (See Refs. 52, 53, and 64, and the later-published data in Ref. 65.) Comparisons were made with re-analyses of data from the Aerotrain experiments and from static and flight data supplied by Pratt & Whitney Aircraft and Douglas Aircraft Company (see Ref. 66 and the later-published report in Ref. 67) using the JT8D-109 NASA refan version of the low-bypass-ratio JT8D turbofan engine on a DC-9-30 and the high-bypass-ratio JT9D-59A on a DC-10-40. Stone's analytical method, as it existed at the time of the Conference, was indicated to be able to generate closer predictions of the wideband jet-mixing noise level in flight than the method using the m-exponent of the velocity ratio. Procedures used for removing internal noise contributions were discussed in detail. Subsequent to the Conference, Stone continued development of a flight-effects prediction method as discussed in the next Section.

[illegible] result of Stone's presentation was the prediction of no increases [illegible] mixing noise in the forward arc as a result of flight effects. The

jet mixing noise was predicted to be lower in flight at all angles than the projected data from static-engine noise measurements with the largest reductions occurring in the aft, or exhaust, arc. No amplification, or forward-arc lift, of jet-mixing noise was predicted. Predictions of increases of jet mixing noise in flight (relative to projections from static measurements) were considered by Stone to result from improper removal of noise produced by internal engine noise sources or airplane installation effects.

This viewpoint was debated at some length at the Conference. The importance of airplane-installation effects on engine noise was emphasized by Bryce of NGTE. Experimental evidence supporting the importance of installation effects was demonstrated later by model tests conducted at NGTE, and described later in this Section, and by Low of Douglas Aircraft Company.

4.2.5 *Douglas Aircraft Company*

J. K. C. Low of the Douglas Aircraft Company component of the McDonnell Douglas Corporation presented results of analyses conducted under contract to NASA Lewis Research Center of the effects of forward motion on the low-frequency noise produced by the JT8D-109 NASA Refan on a DC-9-30, by the JT9D-59A on a DC-10-40, and by the CF6-6D on a DC-10-10. The results presented at the Conference were in the nature of a progress report. The final report was published in October 1977.[67] See also Ref. 68.

The methods used by Low were described as being based on curve-fitting techniques to derive estimates of the spectral components of jet-mixing noise and "core" noise. The techniques were applied to 1/3-octave-band sound pressure levels measured around an engine operating on a static engine test facility and 1/3-octave-band sound pressure levels obtained from flyover noise tests. The curve-fitting techniques were coupled with assumptions about the variation of the level and spectral shape of jet and "core" noise with primary jet velocity and sound directivity angle, (b) about atmospheric propagation effects, (c) about differences between the relative strengths of the jet and "core" noise sources at different engine power settings, (d) about the level and spectrum of noise due to nonpropulsive aircraft noise sources and (e) about the level and spectral shape of low-frequency broadband noise radiated from the inlet

and fan-discharge ducts relative to the calculated spectral levels of jet and "core" noise. These assumptions permitted Low to establish estimates of the separate strengths of jet and "core" noise spectral components at a number of angular locations along a circular arc and over a wide range of engine power settings.

The jet and core noise spectra were derived from 1/3-octave-band sound pressure levels at band center frequencies from 50 to 1000 Hz. For the portion of the spectra at band center frequencies greater than 1000 Hz, the measured sound pressure levels were assumed to be controlled by turbo-machinery noise sources. The derived jet and core noise spectra were rolled off at arbitrary rates of 4 to 6 dB per octave starting in the band at 1000 Hz. Wideband, or overall, sound pressure levels were calculated from the spectra determined for the resulting low-frequency jet and core noise under static and flight conditions.

Various details of the noise-source separation methods were presented. The effect of forward motion on the amplitude of the wideband low-frequency sound pressure level was discussed in terms of m-exponent approach of Eq. (25). Figures 26 and 27 (from Ref. 67) were presented to show the data derived from the JT8D-109/DC-9-30 and JT9D-59A/DC-10-40 tests. The wideband sound pressure levels were adjusted to a common radial distance of 45.7 m.

The JT8D-109/DC-9-30 results in Fig. 26 showed positive m values (or lower noise levels in flight than under equivalent static conditions) at all angles. A similar trend was noted for the JT9D-59A/DC-10-40 results in Fig. 27 at the high power settings and with the 11-deg flap deflection, some negative values were noted for exponent m at angles in the forward quadrant, thereby implying amplification of the low-frequency noise levels at these angles for that airplane configuration.

The negative values for exponent m in the forward quadrant that were obtained for the 54-deg landing-flap setting were considered to result from a low-frequency noise source not accounted for during the analysis. That source was considered to be associated with flow from the fan-discharge ducts of the high-bypass-ratio turbofan engines mounted on pylons below and ahead

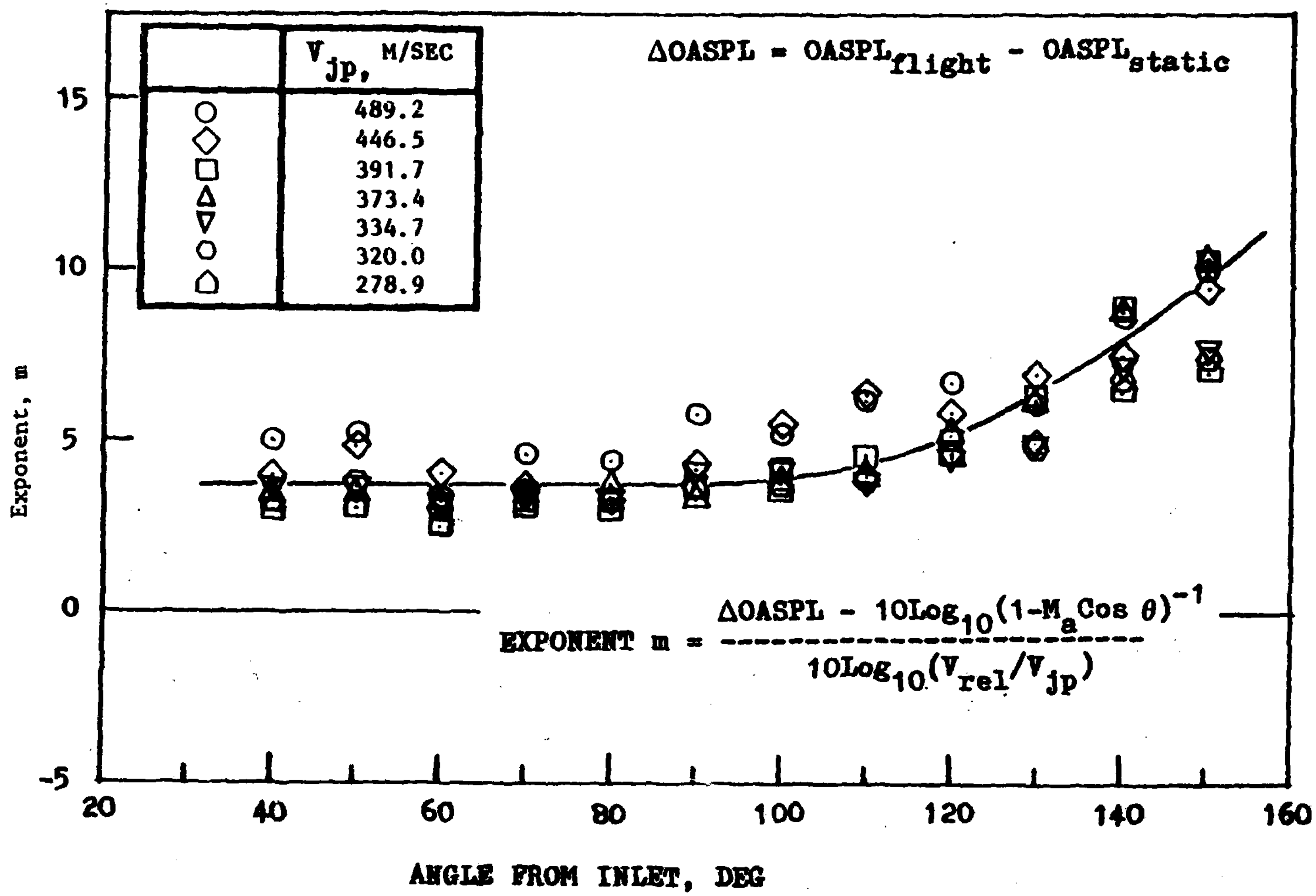


Figure 26.-Velocity exponent m derived from JT8D-109/DC-9-30 low-frequency noise data, ground microphone at 45.7-meter radius, single engine, refs. 67 and 68.

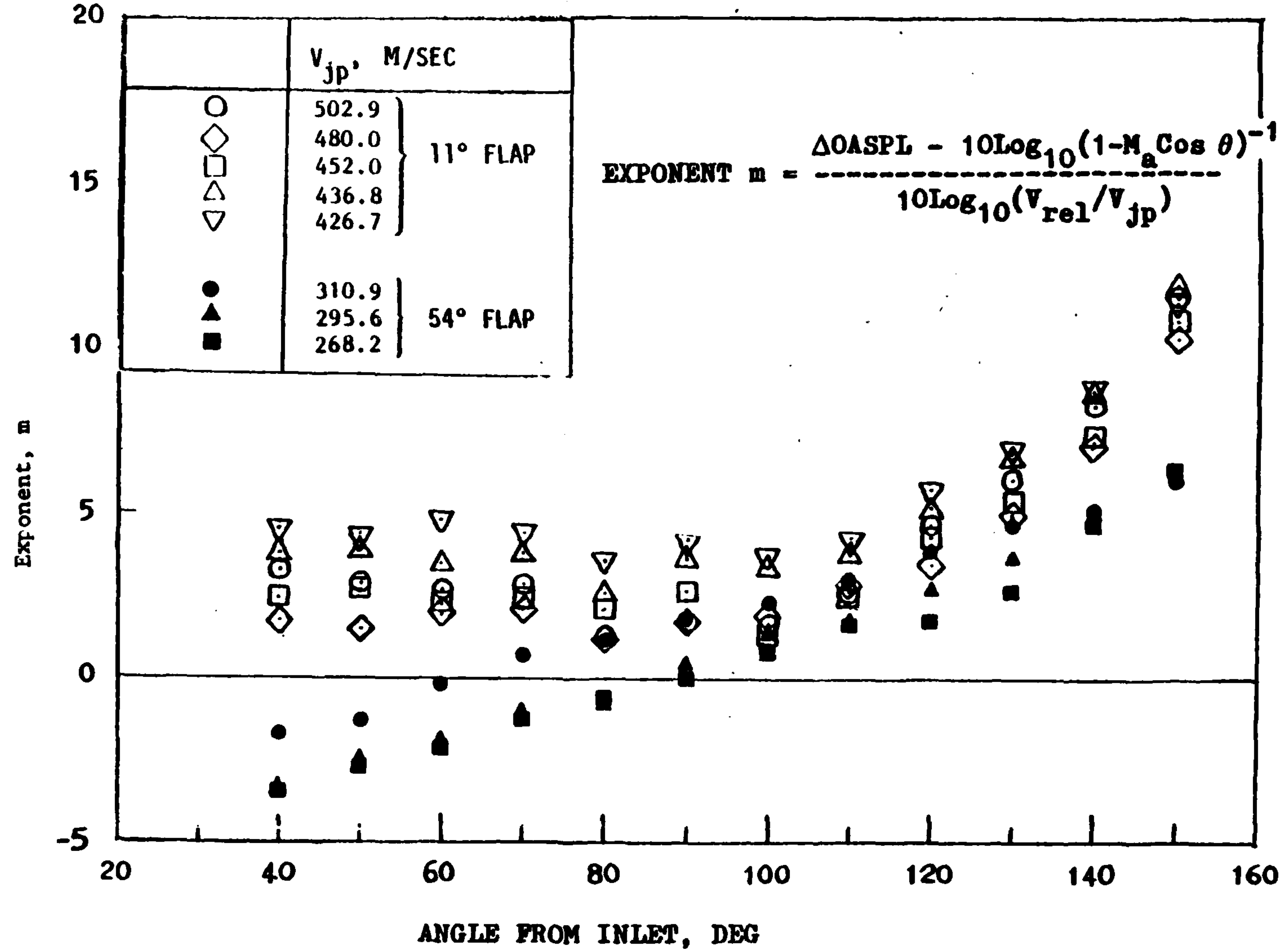


Figure 27.-Velocity exponent m derived from JT9D-59A/DC-10-40 low-frequency noise data, ground microphone at 45.7-meter radius, single engine, refs. 67 and 68.

of the wing. With the flaps deflected to 54 degrees, the fan-exhaust jet impinges on the flap in the region of the jet-exhaust gate in the flap. The flow over the surfaces of the flap and various edges in the gate area could generate low-frequency noise similar to that produced by lower-surface-blown flaps used to provide powered lift for a STOL aircraft.

The results presented by Low were taken as another indication that aircraft installation effects are important in the determination of the effect of forward motion on jet and combustion noise.

4.3 Presentations at the AIAA 5th Aeroacoustics Conference

Significant advances were made since the DOT/FAA Conference in the ability to explain why there were differences in the predicted effect of flight on the level and directivity of low-frequency, broadband noise produced by a jet-propelled aircraft in flight depending on whether the prediction was based (1) on model tests in a laboratory, (2) engines tested statically and in a wind tunnel, or (3) engines tested statically with the noise measurements then projected to equivalent flight conditions and compared with aircraft noise measurements. Improvements were also made in model-scale acoustic test facilities used for studying forward-motion effects and in the ability to account for differences between the aeroacoustic characteristics of a jet in a flight-simulation facility and on an aircraft. In this Section we review some of these advances in the art of predicting the effect of flight on jet-mixing noise and engine internal noise sources.

Presentations made at the AIAA 5th Aeroacoustics Conference in March 1979 described important advancements in predictions of static-to-flight effects. There were, however, a number of related presentations or publications between the time of the February 1977 DOT/FAA Conference and the March 1979 AIAA Conference. These results are also reviewed here in approximately chronological order.

One factor that was not discussed in depth at the February 1977 Conference

was the ability of noise sources and aerodynamic disturbances upstream of the jet-nozzle exit to excite the jet stream and to cause the far field noise levels to be higher than they would have been without the upstream disturbances. These effects on the level of jet noise, while not strictly flight effects, are potentially important in understanding the differences between flight effects predicted on basis of model-scale and full-scale tests.

Bechert and Pfizenmaier[69] at DFVLR in West Germany conducted some model-scale tests in the early 1970s and showed that a jet could be excited by a pure-tone sound so as to amplify the broadband jet noise. Moore[70] at Rolls Royce showed that shear waves near the boundary of a jet just downstream of the nozzle exit could be excited by acoustic, aerodynamic, and laser sources. The shear waves grow in an unstable fashion in the downstream direction, affecting the turbulent structure of the jet, and the radiated noise level.

Deneuville and Jacques[71] reviewed the problem of the amplification of jet noise in a paper presented at the 4th AIAA Aeroacoustics Conference in October 1977 and described results of studies conducted at SNECMA. The influence of upstream acoustic or aerodynamic disturbances was considered to be important in determining jet noise levels in actual engine installations.

Publications and presentations in 1977 and 1978 related to measurements and prediction of flight effects included Cocking[50,72] of NGTE using data derived from model-jet tests in 1975 and Brooks[73] of Rolls Royce who described results from a carefully conducted series of flyover noise tests using a military jet trainer (a Jet Provost) powered by a single Rolls Royce Viper turbojet engine.

The Jet Provost tests used microphones mounted on poles about 20 ft above the tops of the two 450-ft-high towers that supported a bridge across a river. This arrangement permitted measurement of essentially free-field sound pressure levels over the frequency range of interest. The airplane was flown at constant engine power settings at various heights over the microphones. The engine and its long tailpipe was also mounted on an engine test stand for static noise testing. The data from the static and flight

tests form an important data base.

The results showed that projections from the static to flight conditions indicated higher levels of low-frequency noise in the forward quadrant than actually measured. In the rear quadrant, low-frequency noise reduction due to forward motion was less than predicted. The Jet Provost data and the data from the earlier tests reported by Brooks and Woodrow[55] on a HS.125 business jet, powered by two Rolls Royce Viper engines, provided two of the three principal sources of flight data for subsequent investigations at NGTE of installation effects on aircraft noise. The third data source was from tests using the Rolls Royce spinning rig to simulate forward motion.

Two other papers at the 4th Aeroacoustics Conference relevant to flight effects were by Low[68] and Way[74]. The essence of Low's paper was given at the February 1977 DOT/FAA Conference and was highlighted in the previous Section. The main contribution was an indication that a significant amount of low-frequency, broadband noise may result from an interaction between the exhaust flow from the fan-discharge ducts and the trailing-edge flaps when the high-bypass-ratio engines on the DC-10 are at a low power setting and the flaps are fully deflected and the exhaust gate in each flap is open; for more details see Ref. 67.

Way[74] of NGTE described a modification of NGTE's flight-simulation test facility that subsituted a free-jet, or co-flowing airstreams, for the large open-throat wind tunnel that had been used for earlier test programs.

Stone of NASA-Lewis Research Center continued his studies of the effects of flight on jet and combustion noise. He presented papers at meetings of the Acoustical Society of America in December 1977 and May 1978. The flight effects portion of the December 1977 paper[65] was reviewed at the DOT/FAA Conference and was discussed in the previous Section. In the May 1978 paper[75], Stone showed that the method for predicting flight effects based on exponent m did not agree with experimental data as well as a modified method developed at NASA Lewis. This theme was refined and extended in a paper at the 5th Aeroacoustics Conference. That paper[37] was described in the Jet Noise Section in the context

of an inverted-velocity profile jet. Stone's analysis indicated procedures to account for the presence of, and the effect of flight on, engine internal noise sources (or combustion noise) and shock noise at high engine power settings may not have been adequate for the full-scale test data and were the main reason for differences between predictions of flight effects derived from model and full-scale tests.

The two other major publications before the March 1979 AIAA Conference were the Septenber 1978 review by Bryce[42] of flight effects studies at NGTE and the October 1978 report[76] by researchers at the Lockheed-Georgia Company. The NGTE presentations at the February 1977 DOT/FAA Conference are included in Ref. 42. Material contained in the two NGTE flight-effects papers at the 5th Aeroacoustics Conference was taken from the September 1978 review report.

The Lockheed report in Ref. 76 describes tests conducted under contract to NASA-Lewis in Lockheed-Georgia's flight-simulation test facility. The facility uses a free jet around a model nozzle in an anechoic room. The authors (Ahuja, Tanna, and Tester) also presented a paper[77] at the March 1979 AIAA Conference using results extracted from their NASA Contractor Report. The basic objective of the Lockheed study was to investigate the influence of upstream noise sources and noise produced by shocks downstream of the nozzle on differences between measured and predicted in-flight noise levels. A principal result from their study was that jet-mixing noise was reduced in flight at all angles. Noise from internal, or upstream, sources was not reduced in flight as much as the jet-mixing noise and thus was considered to be a major factor in differences between static-to-flight effects derived from model-scale laboratory tests and full-scale engine and airplane tests.

The rest of this Section describes results from papers presented at, and subsequent to, the March 1979 AIAA Conference.

Schlinker and Amiet[78] of UTRC presented results from a study done for NASA-Langley Research Center. They extended Amiet's previous analysis for the scattering experienced by a sound wave propagating through the turbulent shear layer of a free jet used as a flight simulator in a laboratory experiment.

Strout of Boeing and Atencio of NASA-Ames continued investigations of jet noise suppressors using a JT8D-17R engine as a jet noise source[79]. The engine was tested with a flow-inverter system to force cooler fan-discharge flow down toward the engine centerline and hotter turbine-discharge flow outwards toward the wall of the nozzle. A 20-lobe internal-mixer nozzle and an acoustically lined shield downstream of the nozzle were also tested. Tests were conducted on an engine test stand and with the engine in the NASA 40 by 80-foot wind tunnel. The multiple-sideline-technique described previously was used to locate noise sources and derive flight effects.

Szewczyk[80] of Rolls Royce presented a paper on the effects of flight on coaxial jet noise. His results indicated that the relationship between relative-velocity exponent and directivity angle derived from scale-model laboratory tests would agree with full-scale tests of coaxial jet engines when account was taken of internal noise, installation effects, and the axial distribution of sources of jet-mixing noise.

He also concluded that forward-arc increases in noise in flight were the result of nonpropulsive aircraft noise sources, or airframe noise, at high forward speeds even with the aircraft in a clean configuration with wing leading-edge slats and trailing-edge flaps retracted and landing gear stowed. With slats extended and flaps deflected, the contribution of low-frequency airframe noise was a major factor in the forward-arc noise levels at high engine power settings, and was a controlling factor at low engine power settings.

Szewczyk also pointed out that many (probably most) of the previous measurements of aircraft noise were not especially suitable for studying static-to-flight effects over a range of sound propagation angles. Many flyover noise measurements were (and are) made with a microphone at a height of 1.2 m above the ground surface. Ground reflection effects introduce large spectral irregularities that vary with time during the flyover. The spectral distortions are most severe at low frequencies and make it difficult to obtain meaningful comparisons of flight and projected static data. Attempts to use ground-plane microphones, in order to eliminate ground-reflection effects, have not always been successful because most attempts have used a microphone lying on, or mounted perpendicular to, a board. The change in acoustical impedance and

diffraction effects that occur at the edge of the board (which for practical reasons is never very large in extent) cause phase changes which distort the spectrum for grazing sound waves. Szewczyk recommended the use of microphones mounted on 10-m poles to minimize ground-reflection effects in the frequency range of interest and over a wide range of angles. Ensemble averaging of several nominally identical flyover noise measurements was also recommended to increase the statistical confidence in the flight data. Ground-plane microphones could be used for low-frequency measurements if the ground surface was acoustically hard and large in extent.

Szewczyk also pointed out that many flyover noise measurements were not accompanied by detailed measurements of engine performance parameters. The analysis of static-to-flight differences had been shown to be sensitive to predicted relative levels of jet mixing noise and combustion noise at the various sound directivity angles. Some of the difference between the static-to-flight effect predicted from model tests in a laboratory and derived from full-scale engine and airplane noise measurements was shown to be the result of inaccurate estimates of critical paramenters such as jet velocities, airplane angle of attack, and the angle between the jet thrust axis and the flight path.

For the measurements of static engine noise levels, Szewczyk pointed out that an often-ignored problem was the distributed nature of the sources of jet noise and that many measurements around a stationary jet engine had not really been made in the acoustic far field for low-frequency jet-mixing noise. If the effective acoustic source is taken to be the center of the nozzle exit for all frequencies, instead of some axial station downstream of the nozzle exit, then projections of the static data to equivalent flight conditions may be lower than they should be. The calculated static-to-flight differences will then be smaller than if more-accurate estimates of source locations are used for extrapolating the static measurements to flight conditions.

D. J. Way and W. D. Bryce from the National Gas Turbine Establishment (NGTE) in England both presented papers at the Fifth Aeroacoustics Conference. The papers contained new findings on installation effects on jet and combustion noise.

Way[81] described the results of a series of experiments designed to investigate systematically the effects of placing a flat, square plate upstream of the nozzle exit of a model jet immersed in the flow from a free-jet flight-simulation facility. Bryce[82,42] reported on installation effects associated with two specific flight tests and with flight-simulation tests using the Rolls Royce spinning rig.

The experiments reported by Way were conducted in NGTE's acoustic test facility[42]. The parameters that were varied included (1) jet velocity and simulated flight speed, (2) jet total temperature, (3) the radial position of the plate, and (4) the axial position of the plate. The plate was always oriented perpendicular to the free-jet flow with its center perpendicular to the jet axis. The plate was always upstream of the exit of the nozzle plane of the model jet. The frequency range for the noise measurements was covered by 1/3-octave bands with center frequencies from 500 to 31,500 Hz for most test cases.

The general result of the study was that turbulence in the wake from the plate interacted with the flow field of the jet to produce significant increases in the level of broadband noise relative to the level measured when the plate was removed. The effect of the plate on far-field noise levels was only apparent during the flight-simulation tests with airflow from the large, free jet around the model nozzle. No increases were apparent when tests were performed under simulated static conditions with no flow from the free jet.

The flow around the flat plate was found to produce broadband sound that was generally well below the level of the broadband sound measured when the model jet was operating. At low model-scale frequencies (the 500 to 2500-Hz bands) and in the forward quadrant, however, the plate-alone noise was relatively close to the noise measured with the jet operating.

The effect of the plate on the far-field noise levels was observed to be approximately constant over the frequency range of the spectrum at each angle and test conditions. Changes, then, were summarized by changes in wideband jet noise level. The frequency bands included within the wideband noise level were limited to those at, and above, center frequencies of 3150 Hz

to avoid contamination from the noise produced by the air flowing around the plate.

The key results are shown in Figs. 28 and 29. Figure 28 shows the effect of locating the plate in various radial and axial positions. The solid lines show noise levels measured with the jet alone under static and simulated flight conditions.

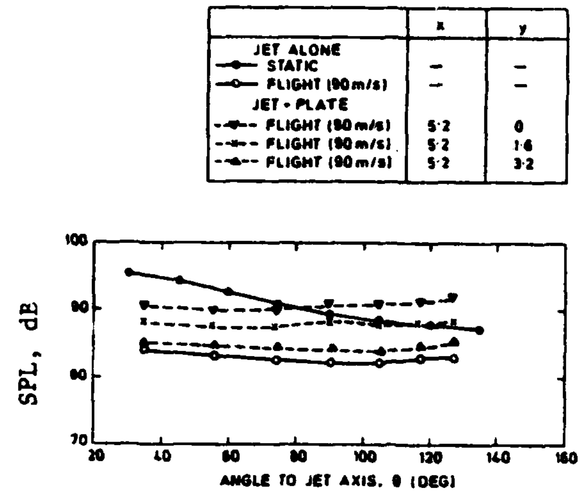
Figure 28(b) shows that variation of the axial location of the plate (from 1.2 to 9.1 nozzle diameters upstream of the nozzle exit) had only a small effect on the far-field levels. Variation in the radial location of the plate, Fig. 28(a), however, produced large differences in the far-field wideband noise level.

As the plate was moved outward away from the jet pipe, the effect of the plate on the measured levels was rapidly reduced. With the plate 3.2 nozzle diameters out from the jet pipe, the far-field wideband noise level was almost equal to that measured under flight conditions with the plate removed.

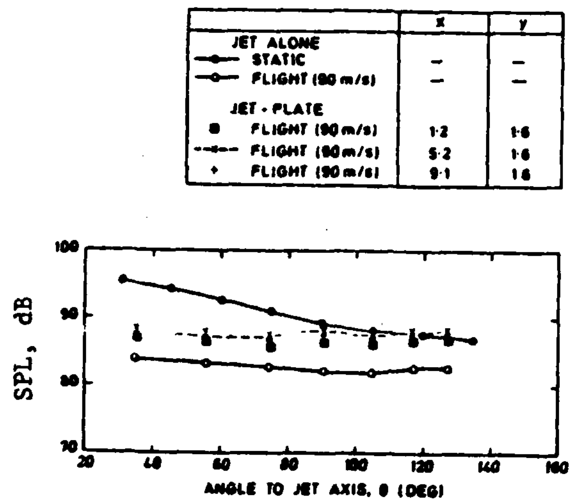
The explanation for the observed effects was considered by Way to be related to the rapid decrease in the intensity of the turbulence in the wake from the plate interacting with the jet as the plate was moved radially outward. The rate of decrease of the turbulence in the plate's wake would be less in the axial direction than in the radial direction.

With the plate touching the jet pipe, the noise level measured in the forward quadrant under simulated flight conditions was higher than measured under static test conditions, see Fig. 28(a). This result indicated actual amplification and not simply a reduction of the flight effect that would otherwise be present.

In commenting on the similarity between the results of the flat-plate, or bluff-body, tests and those obtained using the J-85-powered Aerotrain[57], Way pointed out that the aft section of the nacelle around the J-85 had been equipped with a trip ring (an annular obstacle) in order to assure separation



(a) with radial position



(b) with axial position

Figure 28.-Variation of jet noise SPL in flight with position of the plate ($V_j \sim 303$ m/s, $T_j \sim 293$ K), ref. 81.

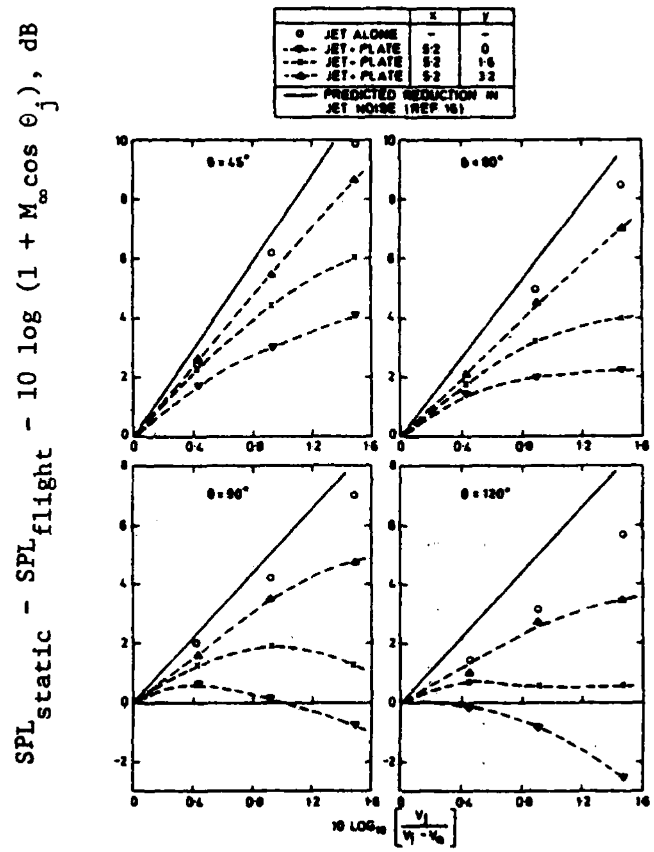


Figure 29.-Correlation of predicted and measured jet-noise reduction in flight relative to levels measured statically, ref. 81.

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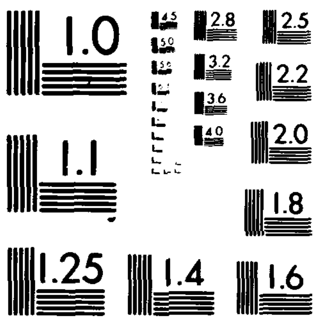


MICROCOPY RESOLUTION TEST CHART

of the boundary layer on the nacelle. The aerodynamic disturbances downstream of the obstacle were considered to have excited the jet and to have been the partial cause of the reduced noise attenuation (resulting from forward motion) in the rear quadrant and the observed increases in noise in the forward quadrant.

A correlation between predicted and measured flight effects is shown by the data in Fig. 29 for the case when the plate was 5.2 diameters upstream of the nozzle exit. The ordinate is the difference between the wideband sound pressure level (the combination of 1/3-octave-band sound pressure levels for center frequencies of 3150 Hz and higher) measured under static and simulated flight conditions as adjusted by a relative-motion factor. The abscissa represents the velocity ratio and the solid line in Fig. 29 is the predicted relationship between the ordinate and the abscissa, the slope of the line being the exponent m of Eq. (25) by the method of Ref. 72.

Figure 29 illustrates two results. For the data measured with the jet alone (open circles), the sound pressure level measured under flight conditions was less than that measured under the static condition, but by less than predicted. The difference between the predicted and the measured flight effect for the jet-alone noise increased as the directivity angle varied from the rear to the forward quadrant. The measured correlation between the ordinate and the abscissa could still be represented by a line of slope m except that the value of m would be a function of directivity angle.

For the data measured with the flat plate installed, the effect of flight was a nonlinear function of jet and flight speed, sound directivity angle, and plate radial location. The simple, exponent approach of Eq. (25) is clearly not adequate to account for installation effects such as those associated with a bluff body upstream of a jet nozzle. Such effects could, for example, be associated with the flow around an engine pylon interacting with the jet exhaust. Also, the wake from wing trailing-edge flaps (at landing-approach deflections) could impinge on the jet exhaust from fuselage-mounted engines. Flyover noise data often used for estimating flight effects on jet noise may easily have included interaction effects similar to those measured in these laboratory flight-simulation tests. It was also noted that flight-simulation research facilities may contain bluff surfaces in the flow field upstream of

the jet nozzle and that the wake from these surfaces can affect the aerodynamic conditions around, and in, the jet exhaust.

The paper by Bryce[82] traced the history of research at NGTE on the effects of flight on jet engine noise. Facilities and results of investigations from 1972 to 1977 were discussed earlier in this Section.[42] In 1977 and 1978, NGTE carried out a series of experiments in their new Noise Test Facility that provided insight into some of the acoustic and aerodynamic effects on jet engine noise when an engine is installed in an airplane.

The results of two controlled flight tests[55,73] were examined in 1975 to see if the differences between (1) the measured flyover noise levels and (2) static noise measured around an engine and extrapolated to common conditions could be predicted on the basis of estimates of the relative levels of, and the effects of flight on, jet mixing noise and engine internal noise. Substantial discrepancies existed over a wide range of angles (particularly in the forward quadrant) between the predicted and the measured effects of flight on jet engine noise.

An attempt to resolve the problem was made using the Rolls Royce spinning-rig flight simulator and an outdoor free-jet flight simulator at NGTE. A model nozzle having a kerosene-burning combustor upstream was tested in both facilities. The test demonstrated that there were significant differences in the observed flight effects. It was concluded that the reason for the difference lay in the installation of the model nozzle on the rotating arm of the spinning rig and not in the different test facilities.

In 1976, NGTE built a 1/9 scale model of the aft portion of a HS.125 business jet. The model was installed in an anechoic chamber near the exhaust of a heated air jet. The hydrogen burner used to heat the jet produced a strong tone at 1600 Hz.

When the model of the aft portion of the HS.125 was moved into position near the jet, the far-field noise levels were increased, especially in the forward quadrant (in the flyover plane) where as much as a 12-dB increase was measured. Most of the increases were in the 1/3-octave bands containing the

fundamental and second harmonic of the burner-related tone. Some increase in broadband jet noise was also measured.

To investigate the cause of the increases, the model was tested in segments. The fuselage portion of the model was found to increase the burner tone level by about 3 dB at an angle of 90° and the jet noise by about 1 dB. The major cause of the increase in the level of the burner tone and jet noise was found to be the horizontal fin, or tailplane, which, on the HS.125, is mounted at the tip of the vertical fin in a tee-tail arrangement.

Since the horizontal fin was about six nozzle diameters above the axis of the jet, no interaction noise from jet exhaust impingement was considered to be present. The increase in the noise levels in the forward arc was attributed to a scattering mechanism whereby some of the sound that propagates up toward the tailplane was scattered downward and forward to increase the levels measured in the forward quadrant. Since sources of jet noise tend to be mostly located well downstream of the nozzle exit while the burner noise source is upstream of the nozzle exit and hence has an effective location near the nozzle exit when it radiates sound to the far field, the scattering hypotheses could explain the larger effect on the burner tone than on the broadband jet noise.

The experimental results just described, while conducted only under static conditions, were interesting because they revealed an installation effect not previously considered. In 1977, the new Noise Test Facility at NGTE became operational and research studies of installation effects on jet engine noise were continued. The previous paper by D. J. Way[81] described some of those studies. In this paper, Bryce[82] describes experimental results obtained in the new facility that are applicable to models of the HS.125, the Jet Provost, and the Rolls Royce spinning rig. The feature of the new test results is that they were conducted in a large anechoic chamber with the flow of a free jet around the model nozzle and models of the airplane or rig hardware.

Internal engine noise sources were simulated by a loudspeaker. To

obtain measurable signal-to-noise ratios, the loudspeaker was driven by sinusoidal signals. For practical reasons, the frequency range of the signals was limited to 1000 to 4000 Hz; higher frequencies (or a wideband sound signal) would have been preferred since the jet noise had components out to 15,000 Hz.

To study the scattering effects associated with an installation such as the HS.125, a model of a horizontal fin was located five nozzle diameters to the side of the model nozzle and at a downstream location similar to that of the HS.125.

Figure 30 shows the model jet nozzle, the surrounding free-jet flight simulator and the model of the horizontal fin. Figure 31 shows the installation effect of the horizontal fin in terms of the changes in wideband sound pressure level with the fin in place and with the fin removed. All tests were conducted with unheated air.

The upper part of Fig. 31 shows the effect of the model tailplane on jet noise, the internal noise source not operating. The effect of the tailplane on jet noise was between 0 and 2 dB under static conditions and somewhat less under simulated flight conditions. The magnitude of the effect was larger in the forward quadrant than in the aft quadrant.

The installation effect of the tailplane on the internal noise is shown in the bottom part of Fig. 31. The effect was large because tones were used and there were strong interference effects, at certain frequencies, between the tones propagating out of the nozzle and sound waves scattered back toward the nozzle from the surface of the model tailplane. The bars in the figure indicate the spread of the results observed at five frequencies between 1000 and 4000 Hz.

A model of the rear fuselage of the single-engine Jet Provost airplane was similarly tested, see Fig. 32. The nozzle is recessed inside the larger-diameter fuselage which also extends a bit beyond the nozzle at the top near the plane of the horizontal fin. Cooling air in the airplane installation flows around the nozzle between the nozzle and the fuselage.

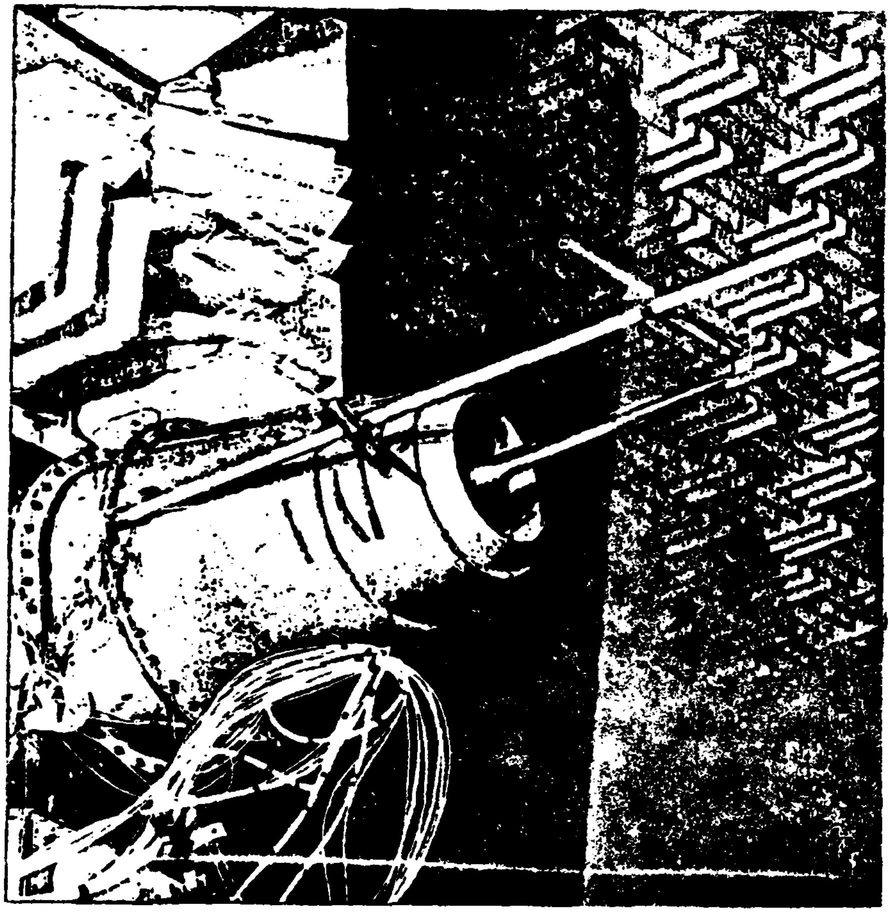


Figure 30.-Model of HS.125 horizontal fin (tailplane) in NGTE free-jet acoustic test facility for flight simulation tests, refs. 42 and 82.

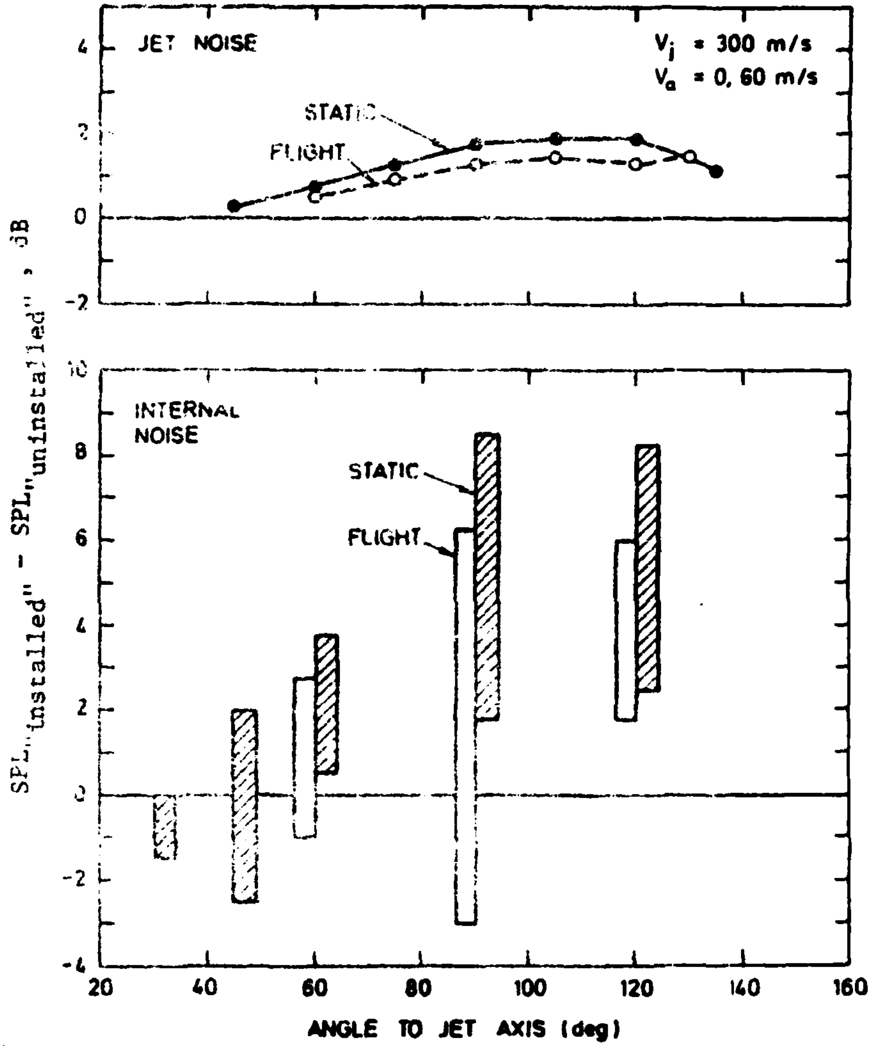


Figure 31.-Installation effects for the HS.125 type of tailplane, refs. 42 and 82.

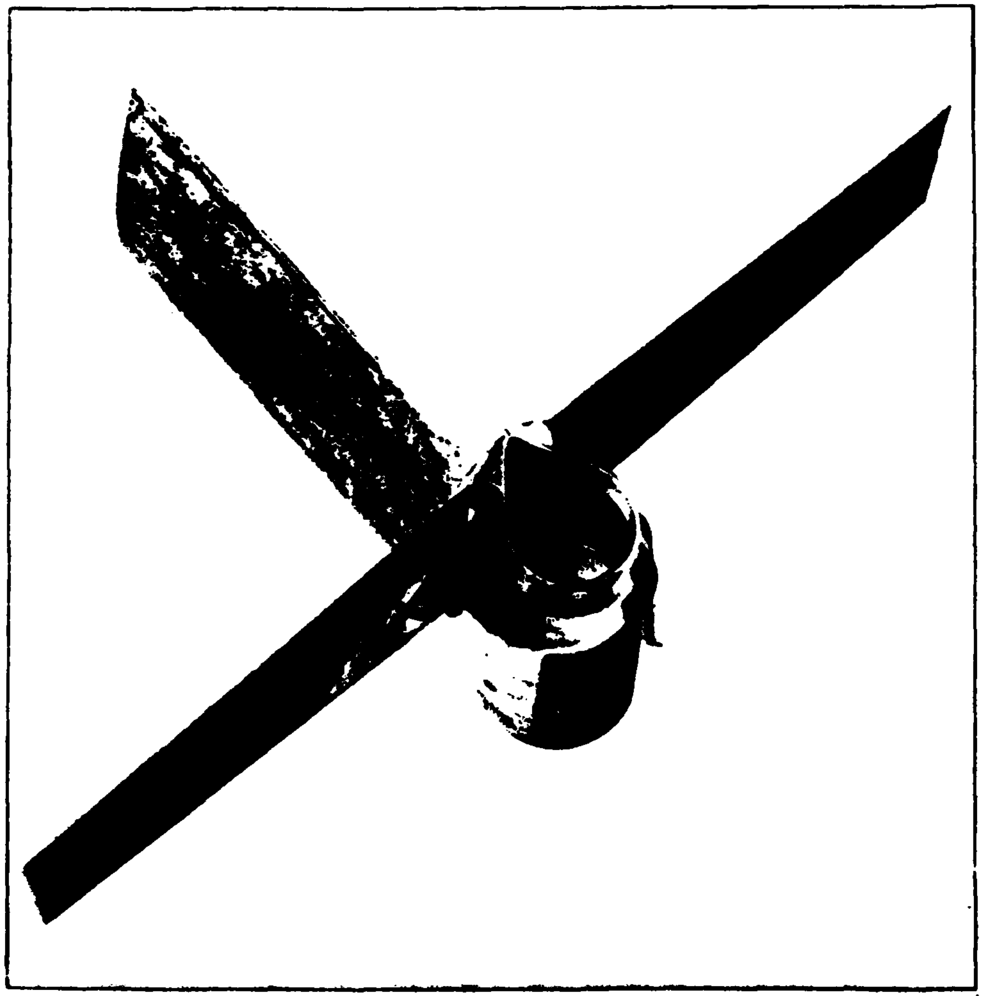


Figure 32.-Model of the rear fuselage of the Jet Provost aircraft, refs. 42 and 82.

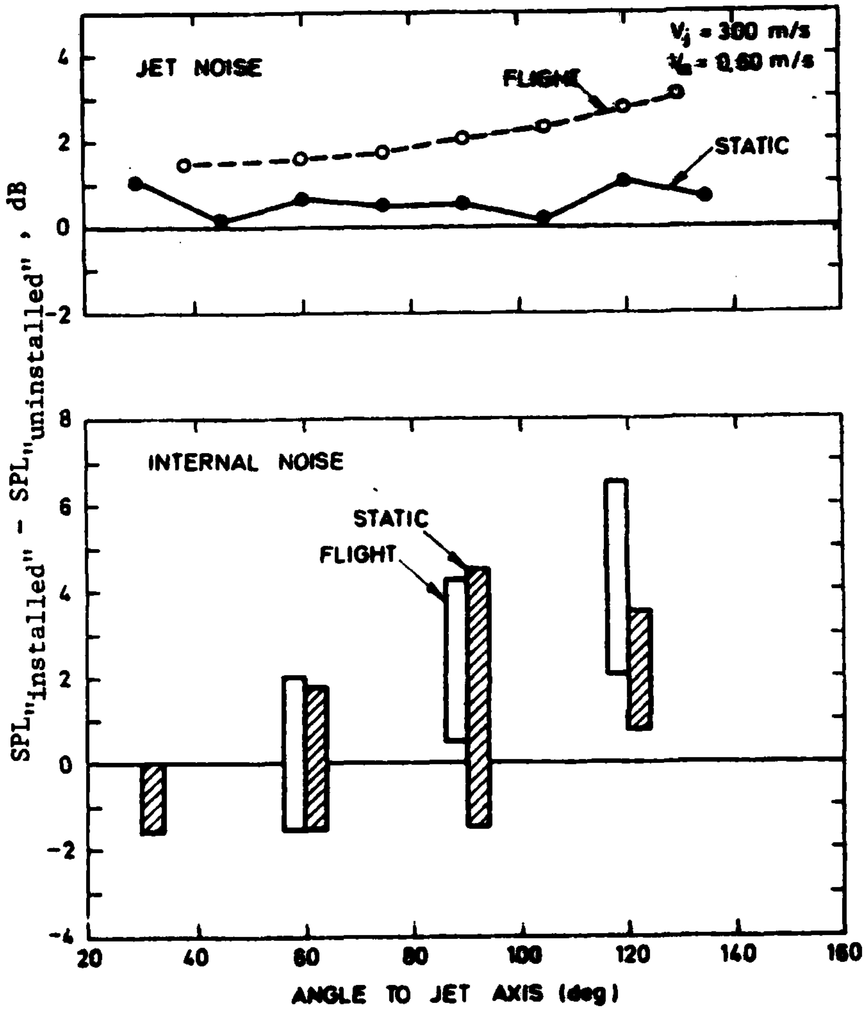


Figure 33.-Installation effects for the Jet Provost model, refs. 42 and 82.

The effects of this installation are shown in Fig. 33 in the manner of Fig. 31. In contrast to the results in Fig. 31 for the model tailplane, the jet noise in flight was increased by the installation relative to the static levels. Changes in internal tone levels were similar to those in Fig. 31. The increase in jet noise was considered to result from aerodynamic excitation of the jet as a result of the impingement and mixing with the jet exhaust of turbulent flow in the channel between the jet pipe and the model fuselage and turbulence in the external boundary layer on the model fuselage. The mechanism here could be similar to those discussed in Refs. 69 to 71.

A model of the Rolls Royce spinning rig was also tested. The actual rig consists essentially of a 10-m-long arm which is free to rotate around a pivot. The arm is propelled by the model jet located at the end of the arm. To help provide a measure of independent control over rotational speed (or simulated flight speed) and jet exhaust speed, flat plates can be bolted to the arm near the tip in order to increase the drag and thus provide a range of flight speeds for a given jet speed.

Figure 34 shows a diagram of the spinning-rig model. The drag plates were placed on the top and bottom surface of the airfoil-shaped arm (or wing).

The installation effect associated with the maximum drag configuration (that of Fig. 34) is shown in Fig. 35. The presence of the drag plates has little effect on the level of the burner-tone noise statically or in flight, but a large effect on the level of jet noise under simulated flight conditions. There was negligible effect on jet noise under the static condition, as was expected. The lack of any significant effect on internal noise was attributed to the lack of any surface downstream of the nozzle exit which could act to scatter the sound as did the HS.125 tailplane model and portions of the Jet Provost model.

The installation effect of the spinning-rig drag plates was considered to be the result of an aerodynamic interaction between turbulence in the wake from the bluff drag plates and the turbulent jet exhaust stream. The result was similar to the results obtained by Way[81] in his study of the effects of jet noise of wakes from bluff bodies upstream of a nozzle exit.

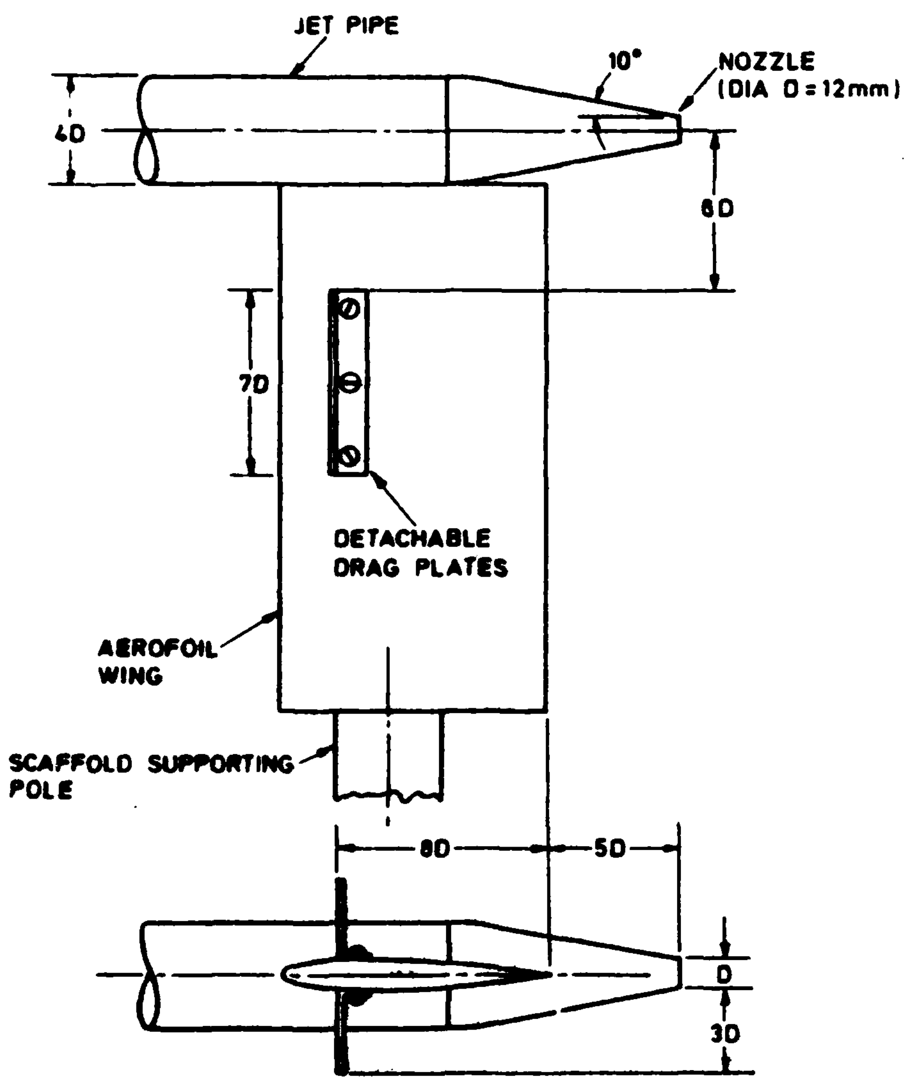


Figure 34.-Diagram of model of Rolls Royce spinning rig, refs. 42 and 82.

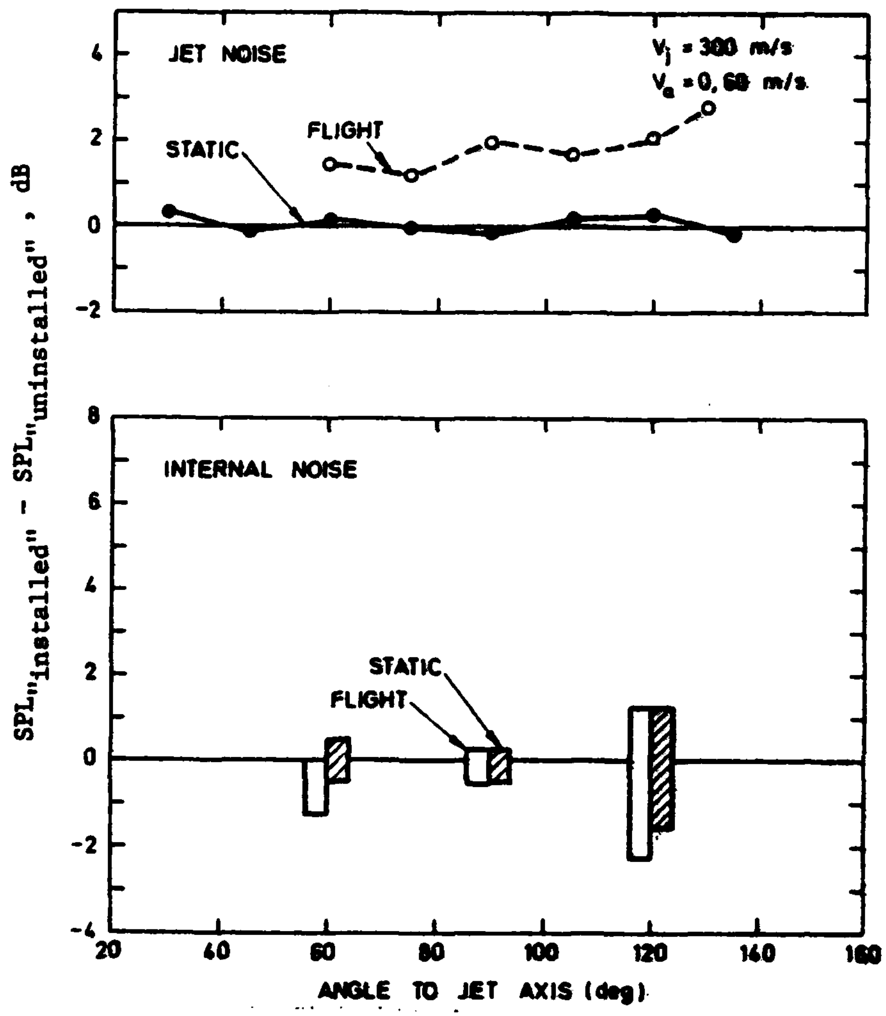


Figure 35.-Installation effects for the spinning-rig model at maximum drag, refs. 42 and 82.

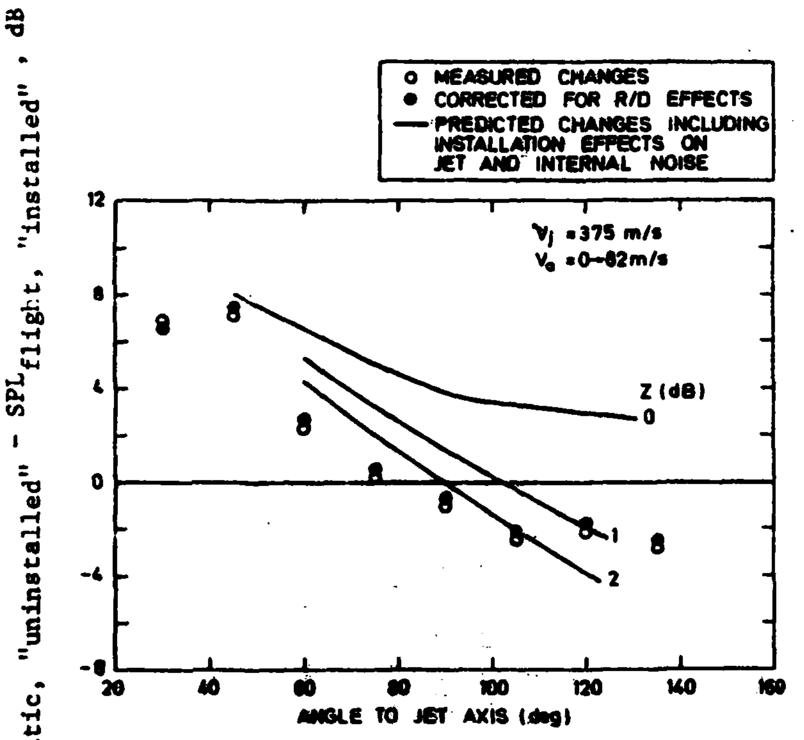
The installation-effect results measured in the laboratory were then used to modify the predictions of the differences between the noise levels measured under static conditions and those measured under flight conditions. The modified predictions were made for the HS.125, for the Jet provost, and the spinning rig. Comparisons of predicted and measured changes are shown in Fig. 36. The measured changes are shown both as-measured and adjusted for the difference in the downstream displacement from the nozzle exit of the effective source of jet noise (so-called R/D effects) under static and flight conditions.

The predicted changes are presented in terms of a parameter called Z. The Z parameter accounts for different relative levels of jet mixing noise and broadband internal noise and was defined as the difference, in decibels at any angle, between (1) the wideband sound pressure level from both noise sources measured under static conditions and (2) the wideband sound pressure level predicted for just the jet-mixing noise under flight conditions. The magnitude of Z represents how much lower the static noise level would be if the internal noise were to be eliminated. Where Z = 0, there is no internal noise and the predicted changes are for jet mixing only. The probable value of Z was considered to be between 0.5 and 1.0 for the airplane installations and the spinning rig.

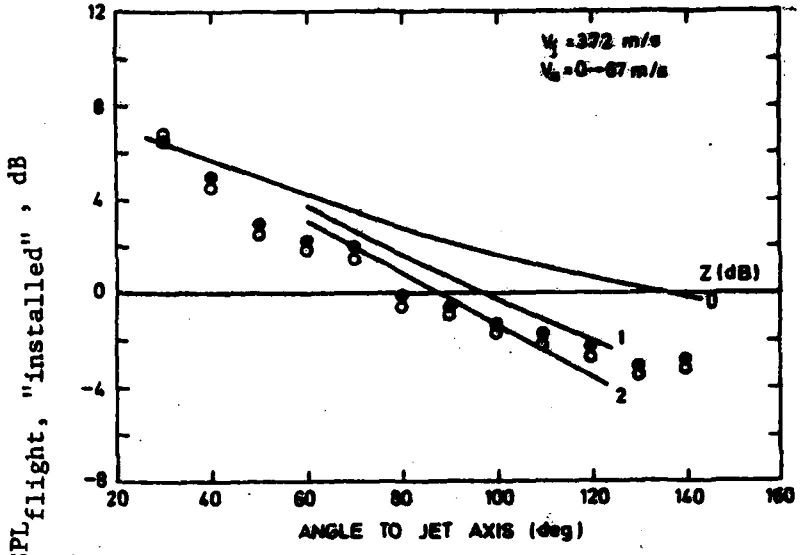
With the tailplane installation effects taken into account, the Z = 1 line in Fig. 36(a) provides a good prediction of the increase in the flight levels over the static levels in the forward quadrant (at 118° and 138°). If scattering from the fuselage (which affected the levels around 90°) had been included, it was felt that the comparisons between predicted and measured flight effects would have been better at other angles.

Comparisons of predicted and measured changes for the Jet Provost are shown in Fig. 36(b). Before inclusion of the installation effect the predictions for the changes between static and flight lay well above the measured changes. The predictions shown in Fig. 36(b) are now quite close to the measured changes.

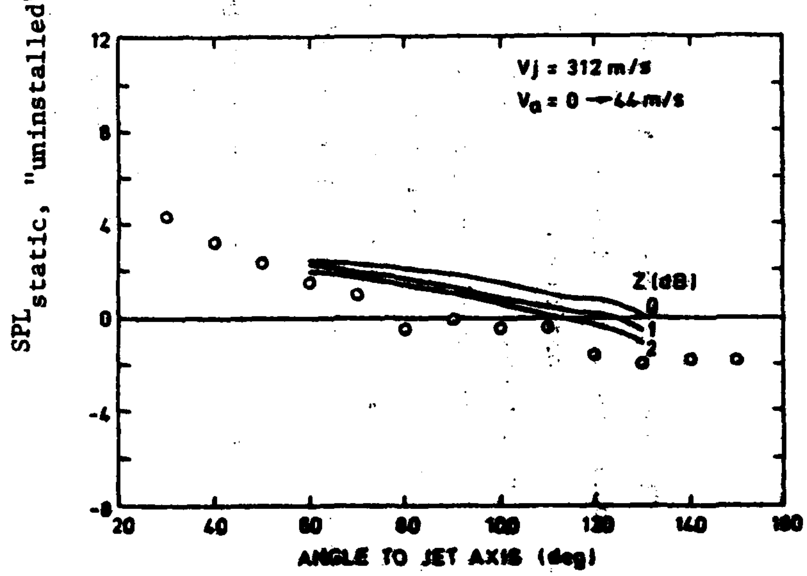
Comparisons for test results from the spinning rig operated in the maximum drag configuration are shown in Fig. 36(c). Over the range of angles between



(a) Viper 601/HS.125



(b) Viper 11/Jet Provost



(c) Rolls Royce spinning rig at maximum drag

Figure 36.-Correlation of predicted and measured jet noise reductions in flight relative to levels measured statically, refs. 42 and 82.

60° and 120°, the predicted and measured flight effects are seen to be in good agreement.

Bryce summarized the results of these studies by noting that predictions of flight effects on jet mixing noise and engine internal noise would require inclusion of appropriate airplane installation effects in order to correctly assess differences between levels measured under static and flight conditions.

This review of flight-effects studies published after the DOT/FAA Conference closes with mention of two papers.

A. Michalke and U. Michel describe a theoretical method for predicting the effect of flight on jet-mixing noise in Ref. 83. Their method is based on a solution to the convective Lighthill equation but does not introduce a special model for jet turbulence.

Their procedure starts with wideband noise measurements made under static conditions at coordinates r, θ_i with respect to the nozzle exit and the upstream or inlet direction. A coordinate transformation is introduced to obtain coordinates r_o, θ_{io} which account for the different path lengths and effective sound directivity angles from the location of the effective source downstream of the nozzle exit.

Thus

$$r_o = r\left[\sqrt{1 - M_\infty^2 \sin^2 \theta_i} - M_\infty \cos \theta_i\right]^{-1} \quad (26)$$

and

$$\cos \theta_{io} = \cos \theta_i \left[\sqrt{1 - M_\infty^2 \sin^2 \theta_i} + M_\infty \cos \theta_i\right] - M_\infty \quad (27)$$

where M_∞ is the airplane or flight Mach number.

The coordinates r, θ_i are related to a coordinate system fixed to the aircraft while coordinates r_o, θ_{io} are for a coordinate system fixed to an observer at rest. Note that $r_o = r$ when $\cos \theta_i = - M_\infty/2$.

For a given M_∞, the effect of Eq. (26) is to make r_o larger than the far-field distance r at angles which generally are in the forward quadrant and smaller than r at angles in the rear quadrant. The angle θ_{io} is always shifted toward the forward quadrant by Eq. (27).

The relation between the in-flight sound intensity, $I(r, \theta_i, M_j, M_\infty)$, at far-field coordinate r, θ_i, jet Mach number M_j, and flight Mach number M_∞ and the sound intensity measured statically, $I_o(r_o, \theta_{io}, M_o)$, is given by

$$I(r, \theta_i, M_j, M_\infty) = \{1 + A[M_\infty/(M_j - M_\infty)]\}^2 \times [1 - M_\infty \cos \theta_{io}]^2 I_o(r_o, \theta_{io}, M_o) \qquad (28)$$

where M_o is a modified jet Mach number under static conditions given by

$$M_o = (M_j - M_\infty)/(1 - M_\infty \cos \theta_{io}). \qquad (29)$$

The directivity of I_o under static conditions should be known as a function of jet temperature for various jet Mach numbers M_j, a requirement that will be difficult to satisfy in practice since there rarely is independent control of pressure (Mach number) and temperature at the nozzle of a jet engine. If the jet temperature under flight conditions is not the same as under the static test conditions, then the variation of the magnitude, as well as the directivity, of I_o must be known as a function of jet temperature for various jet Mach numbers.

The factor A in Eq. (28) is assigned the value 2 by the authors on the basis of a "physical argument".

Michalke and Michel applied their coordinate transformation and level-adjustment method to the static Aerotrain data of Ref. 57 and showed good agreement with the "flight" Aerotrain data for a "flight" Mach number of 0.24 and jet Mach numbers of 1.31 and 1.50.

Nothing was said in Ref. 83 about the effect of flight on the spectrum

of jet noise. All calculations were performed for the wideband sound pressure level, presumably on the assumption that flight effects are constant over the spectrum of jet noise. Also, the examples chosen to demonstrate the method were for supersonic jet Mach numbers where, presumably, the engine noise signal is controlled by jet-mixing noise sources.

At the June 1979 meeting of the Acoustical Society of America, James Stone of NASA Lewis Research Center presented a paper[84] which revised and extended the jet noise flight-effects prediction method of Refs. 64 and 65.

The difference between wideband sound pressure levels under static and flight conditions (at the same distance and angle) is found from

$$L_{WB,\ \theta_i,\ S} - L_{WB,\ \theta_i,\ F} = \Delta_{SO} + \Delta_D + \Delta_K \tag{30}$$

where Δ_{SO} is a factor that accounts for the difference in the strength of the sources of jet-mixing noise when the shear forces at the jet boundary are reduced in flight, Δ_D is a factor that accounts the effect of differences in the dynamic convection speed of the sources of jet-mixing noise under static and flight conditions and the resulting changes in the directivity pattern, and Δ_K is a factor which accounts for the effect of the kinematic translation of the aircraft, relative to a stationary observer, on the amplitude of jet-mixing noise at different directivity angles in the far field under flight conditions.

For typical takeoff and landing flight Mach numbers, the kinematic factor Δ_K results in an increase in the jet-mixing noise level under flight conditions in the forward quadrant of from 0 to 1.5 dB and a decrease in the rear quadrant of 0 to 1.0 dB in comparison with levels measured at the same angle under static conditions. At 90°, Δ_K = 0 dB.

The expressions for Δ_{SO}, Δ_D, and Δ_K are relatively complex and the reader is referred to Ref. 84 for details.

To test the new method for predicting the effect of forward motion on jet-mixing noise, Stone used the data from the J-85 turbojet-powered Aerotrain,[40] and from the test data supplied by Douglas Aircraft Company[67] for the low-bypass-ratio JT8D-109 NASA refan on a DC-9-30 and for the high-bypass-ratio JT9D-59A on a DC-10-40.

The predictions of flight effects were in better agreement with the measurements using the new prediction method than by using the exponent m method for the three sources of data. The exponent m method was also noted to not be universal because the value of the exponent varies with jet velocity, jet density, engine type, aircraft installation, as well as directivity angle, for example, see Figs. 26, 27, and 29. Stone's new prediction method consists of three equations which were considered to be applicable to the jet-mixing noise produced by any jet engine.

4.4 SUMMARY

While there is agreement that the level and directivity of jet-mixing noise and jet-engine combustion noise are different under flight conditions than when measured around an engine or a model jet under static conditions, there still is no agreement on the reasons for the differences or on a method to predict flyover noise levels from static noise measurements.

Because of the large potential payoff, research studies to improve the understanding of the effects of forward motion on jet-engine noise will continue in the 1980s. The benefits include (1) insight into how to design engines to insure the achievement of lower flyover noise levels, (2) removal of a major element of uncertainty from predictions of aircraft flyover noise levels, (3) more-accurate interpretation of the results of engineering development tests conducted under static conditions or in a model-scale flight-simulation laboratory test facility, especially for jet-noise-suppression devices, and (4) an improved understanding of the relative levels, in flight, of externally-generated jet-mixing noise and broadband internally-generated noise from sources such as combustion.

Major advances were made over the seven-year period from 1973 through 1979 in the area of flight effects on jet-engine noise. The advances included development of new laboratory facilities to simulate the effects of forward motion on jet-engine noise. Analytical techniques were also developed to interpret the laboratory results in terms of equivalent full-scale flyover noise levels. Analytical methods were also developed to project static engine noise measurements to equivalent flight conditions and to analyze flyover noise measurements so as to provide meaningful data for comparison with projected static noise data.

Problem areas that remain for flight-effects noise research include (1) reconciliation and improvement of analytical methods for predicting the effects of flight on jet-engine noise;

(2) refinement and improvement of analytical methods for use in interpreting and projecting the results of experiments in laboratory flight-simulation facilities;

(3) development and refinement of laboratory flight-simulation facilities to produce improved simulation of internal jet-engine noise sources and to take advantage of corresponding improvements in analytical methods;

(4) improvement in the understanding and the ability to predict the effects of an engine's installation on the resulting levels and directivity of jet-mixing noise and engine internal noise; and

(5) improvement in practical procedures for measuring and analyzing the transient aircraft noise signals so as to yield more-accurate indications of the spectra of free-field sound pressure levels throughout the duration of an aircraft flyover.

Of the above research areas, the problem of defining aircraft installation effects is of particular concern. Laboratory tests have identified both acoustic and aerodynamic effects. The acoustic effects include sound that is scattered or reflected downward toward the ground. Aerodynamic effects

are associated with excitation and amplification of jet-mixing noise by turbulence in the wakes from objects located upstream of a nozzle and in the external boundary layer on the nacelle of an engine. An aerodynamic cross-flow component over an engine's nacelle, as could occur on delta-wing supersonic transports during takeoff and landing for example, is another example of an aerodynamic installation effect.

Other areas of particular concern are improved methods for distinguishing between internal and external sources of broadband noise (statically and in flight) and improved methods of analyzing flyover noise data to account for atmospheric propagation factors (absorption, refraction, and scattering) and for the distributed nature of sources of jet-mixing noise, especially on large, multi-engine aircraft. Nonlinear propagation effects may also have to be taken into account.

Finally, because of the large number of possible engine-installation arrangements and the wide range of bypass ratios for current and future turbofan engines, additional model- and full-scale experiments would seem to be needed to help develop a prediction method useful for general application.

5. RELATED TOPICS

5.1 Sound Propagation in the Atmosphere

An understanding of the effects of the atmosphere on sound propagation is important to aircraft noise studies. Propagation factors can cause significant alterations in the spectrum of a sound signal at locations which are distant from an aircraft. In terms of the topics reviewed in this report, the importance of atmospheric propagation factors lies mainly in the prediction of aircraft flyover noise levels and in the inverse problem of using measured values of aircraft noise levels to determine levels at locations closer to the aircraft in order to study the effects of flight on jet-engine noise.

The two factors related to sound propagation in the atmosphere that were discussed at the Conference were atmospheric absorption and nonlinear effects associated with high-amplitude sound.

The processes by which acoustic energy is dissipated as a sound wave propagates through the atmosphere have been studied by scientists since the early 1800s. However, molecular relaxation phenomena, which account for most of the absorption, had not been investigated by systematic experiments until relatively recently. In his presentation of research sponsored by NASA Lewis Research Center, Stone described a study that was being done for NASA under the direction of Douglas Shields and Henry Bass at the University of Mississippi.

In that study, atmospheric absorption was measured under controlled laboratory conditions, at frequencies ranging from 4000 to 100,000 Hz, for eleven air temperatures ranging from -18° to +37°C and ten relative humidities ranging from 10 to 100 percent[85]. The results of this detailed experimental study were used to corroborate (and to refine) certain constants in a newly developed theory for atmospheric absorption as a function of frequency, temperature, pressure, and humidity. Excellent agreement was obtained between theory and experiment. The equations describing the absorption of

sound by the atmosphere were incorporated in an American National Standard[86] issued in 1978.

Don Webster from the Applied Research Laboratories at the University of Texas at Austin described some preliminary results of a study of nonlinear effects in atmospheric sound propagation. The basic-research study was jointly sponsored by the Air Force Office of Scientific Research, the Office of Naval Research, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration.

The study was conducted in two phases. In phase 1 (some results from which were presented at the Conference[87]), the effort was essentially limited to discrete-frequency sounds. Many of the experiments in phase 1 were conducted in a 26-m-long travelling wave tube. Outdoor sound propagation experiments in phase 1 were also conducted using tones produced by electrodynamic loudspeaker arrays and by a small siren. The sound source was positioned at the base of an 85-m-tall tower. The propagation path was vertically upwards to avoid ground-reflection problems. An elevator that ran along one side of the tower carried a microphone at the end of a 2.6-m-long boom. Most of outdoor tests were done at night when the wind speed was usually low. The atmosphere was generally warm and humid. The work in phase 2 extended the outdoor propagation tests to narrow and wide bands of random noise, in the frequency range from 2000 to 10,000 Hz, produced by arrays of electrodynamic loudspeakers.

Gustiness of the wind and temperature inhomogeneities caused large, random fluctuations in the signal at the microphone. The magnitude of the fluctuations increased with distance above the ground. Long averaging times were required to obtain meaningful values for the average level of the spectral components; an averaging time of 100 seconds was used for measurements at the longest propagation pathlength (80 m). Waveform pictures, however, could not be averaged and hence waveform comparisons at different distances were subject to more error than the long-term time-averaged sound pressure levels.

The sound pressure levels, at 1 m above the plane of the horns on the loudspeakers, varied from 121 to 145 dB.

One of the main results of the experiments was that the amplitude of the high-frequency portion of the spectrum increased as distance from the source increased.

Nonlinear propagation effects arise because the propagation speed of a high-amplitude sound wave is not just the small-amplitude speed of sound which is a function only of the temperature of the medium. The propagation speed of a high-amplitude (or finite-amplitude) wave varies from point to point on the propagating wave. Therefore, in contrast with an infinitesimal-amplitude or ordinary sound wave, the shape of a high-amplitude wave does not remain constant as it propagates. During a condensation (or compression) phase, the wave shape tends to steepen. During a rarefaction (or expansion) phase, the wave shape tends to spread out. Because of the steepening effect, the level of the high-frequency component of the spectrum associated with the wave tends to increase as the wave propagates.

The steepening of the shape of the wave and the corresponding increase in the level of the high-frequency part of the spectrum of the wave do not continue indefinitely. Eventually, the velocity and temperature gradients in the compression regions become so great that friction and heat-transfer effects become important and counteract the steepening tendency. Once a balance between the steepening effect and the diffusing effect of friction and heat-transfer has occurred, the wave then propagates without further distortion of the waveshape.

For a broadband sound source, the distance that a high-amplitude wave has to propagate before the waveshape stops becoming distorted by nonlinear effects was apparently greater than the approximately 80-m maximum available measurement distance. The amplitude of the high-frequency portion of the spectrum always increased as distance from the source increased. Attenuation by atmospheric absorption [which was minimal under the warm (23° to 31° C) and humid conditions prevailing during the tests] was apparently not enough to overcome the increase in high-frequency energy resulting from nonlinear effects. The level at the spectral maximum (usually around 4000 Hz for the noise sources that were used) tended to decay in accordance with spherical spreading and atmospheric absorption.

A comparison was made between the test spectrum and the spectrum measured at an angle of 150° from the inlet direction at a distance of 76.2 m from a KC-135A aerial-refueling tanker powered by J57 turbojet engines operated on the ground at takeoff power. To make the comparison, the experimental test spectra were scaled down in frequency by a factor of 10 and up in level by a factor of 20 dB. It was noted that although the spectral shapes were somewhat similar (the KC-135A spectrum had much more low-frequency energy), the KC-135A spectrum was about 10 dB higher than the scaled test spectrum in the mid and high frequencies. Since nonlinear propagation effects had been observed with the experimental high-amplitude spectrum it was concluded that nonlinear propagation effects are probably common for jet aircraft. Additional research would be needed to quantify the nonlinear propagation effects and to develop an analytical model suitable for prediction purposes.

5.2 Blown-Flap Noise

Two types of propulsive-lift systems have been considered for jet-powered short takeoff and landing (STOL) aircraft. One system would use high-pressure air bled from engines and exhausted from slots located at the wing trailing edges. This system is termed internally blown flaps (or IBF) or an augmentor wing. The other system uses engines mounted below or above the wings so as to direct, or blow, the engine exhaust onto, or over, the flaps at the wing's trailing edge. The alternate system is known as externally blown flaps (or EBF). Presentations related to noise control for IBF and EBF STOL propulsive-lift systems were given at the 1977 DOT/FAA Conference.

B. H. Goethert and James R. Maus of the University of Tennessee Space Institute (UTSI) had been investigating noise reduction concepts for potential IBF systems. They used a model-scale slot nozzle. Noise reduction by shielding at locations that would be below the aircraft was investigated by positioning the slot-nozzle exit on top of a simulated wing and upstream of the trailing edge.

As an alternative to a slot nozzle, they also tested a linear array of small circular nozzles. To reduce the noise of this arrangement, the UTSI

investigators considered an ejector system downstream of the nozzle exit. The ejector system could be made part of the trailing-edge flaps and could incorporate acoustically absorptive linings to absorb some of the high-frequency acoustic energy near the nozzle exit.

John S. Gibson of the Lockheed-Georgia Company described some results from EBF studies conducted by Lockheed. The studies covered both lower-surface-blown (LSB) flaps and upper-surface-blown (USB) flaps.

To illustrate the concepts studied by Lockheed, Gibson used a review paper[89] prepared for the October 1976 meeting of the International Council of Aeronautical Sciences. LSB systems (as on the McDonnell Douglas YC-15) have special noise sources associated with blowing the exhaust from the primary and fan nozzles onto the deflected flaps. USB systems (as on the Boeing YC-14) have special noise sources associated with trailing-edge flow separation and the resulting turbulence in the shear layer downstream of the flap trailing edge. The YC-15 and YC-14 are prototype versions of advanced STOL transports for military applications.

The Lockheed study was specifically directed at USB configurations and was sponsored by NASA Langley Research Center. Contract results were reported in three volumes: a summary;[90] an experimental report [91] with the acoustic and aerodynamic data; and a report[92] of the analyses.

A few of the results relevant to noise generation and suppression for USB systems are noted here; additional details are given in Refs. 90 to 92.

- The frequency at the maximum of the spectrum is correlated with the length of the USB flow path along the extended centerline of the nozzle from the exit plane to the flap trailing edge;

- The aspect ratio of the nozzle is important in achieving lower noise levels, increasing the aspect ratio (ratio of width to height) from 1 to 8 reduced the sound pressure level at the frequency of the spectral maximum by about 6 dB;

- Nozzle shapes that enhance the spanwise spreading of the flow (reducing the shear forces at the wing trailing edge) also reduced the radiated noise levels;

- Secondary blowing from a slot on the upper surface of the flap just upstream of the flap trailing edge was effective in reducing the USB trailing edge noise by about 5 dB;

- Installing porous material (a felted metal sheet or perforated metal sheets) on the flap's upper surface yielded a small noise reduction; and

- Increasing the simulated forward speed reduced low-frequency USB trailing-edge noise but had little effect on mid-or high-frequency noise except at microphone locations in the aft quadrant behind the wing where the high-frequency noise levels were observed to increase as forward speed increased.

It was also noted that NASA Lewis Research Center was engaged at the time of the Conference in a program with the General Electric Company to develop quiet, clean short-haul experimental engines (QCSEE) for under-the-wing and over-the-wing applications. Papers describing aerodynamic and acoustic characteristics of STOL propulsion systems and aircraft were presented at a NASA Conference in November 1978, see Ref. 93 for details.

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